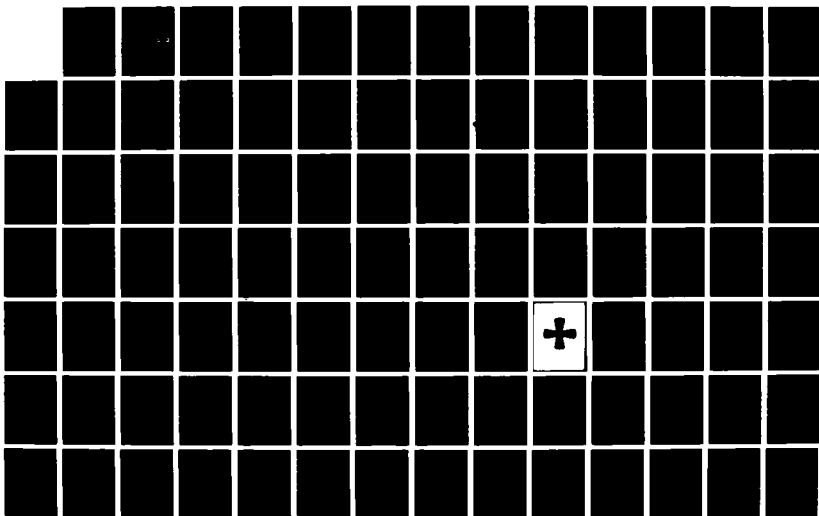AD-A185 861   TARGET SIZE AND LUMINANCE EFFECTS ON ACCOMMODATION AND   1/2
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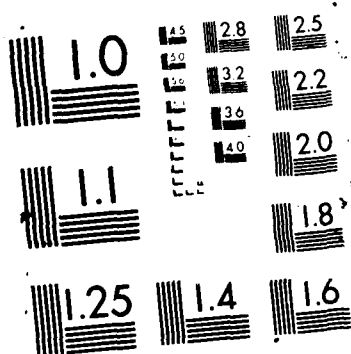   OH L N MCLIN 1987 AFIT/CI/NR-87-88T

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Abstract-- The responses of accommodation and vergence to a changing size stimulus were continuously recorded by means of a dual Purkinje image eye tracker and infrared optometer. These responses were compared to the responses of accommodation and vergence to blur alone and disparity alone. Accommodation and vergence were found to respond in a ratio like the response to blur rather than the response to disparity. This suggests that accommodation is stimulated directly by changing size with vergence responding secondarily as accommodative convergence.

Voluntary effort was similarly found to be consistent with direct stimulation of accommodation and secondary stimulation of vergence. This suggests that voluntary effort may be a component of the response to changing size.

The responses of accommodation and vergence were also measured at different luminance levels to show the effects of luminance on tonic aftereffects of accommodation. After an accommodative stimulus, accommodation may show a tonic aftereffect when the accommodative loop is opened with a pinhole. Darkness has previously been shown to mask these aftereffects.[1] The accommodative aftereffect was found to be reduced or partially masked at mesopic luminance levels. The lower the luminance the greater the masking of accommodative aftereffects.

[1]Schor C. M., Kotulak J. C., Tsuetaki T. (1986) Adaptation of tonic accommodation reduces accommodative lag and is masked in darkness. Invest. Ophthalmol. Vis. Sci. 27, 820-827.

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by

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By

Leon Norse McLin, Jr.

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TABLE OF CONTENTS

Chapter 1

Introduction

To view objects at different distances, the eyes must adjust their direction by changing vergence and their focus by changing accommodation. A change in pupil diameter is associated with the change in accommodation and vergence. The three motor responses are known as the near triad. The near triad is driven by stimuli associated with object distance. Blur is the primary stimulus to accommodation (Phillips and Stark 1977) and disparity (the difference between retinal images) is the primary stimulus to vergence (Stark et al. 1980).

The accommodative system and vergence system do not function independently, but interact with each other. Blur stimulation alone also produces a vergence eye movement, termed accommodative vergence, while disparity stimulation produces a change in the lens focus, termed vergence accommodation.

In addition to these main stimuli of blur and disparity there are other possible stimuli to both accommodation and vergence. These include changes in size, stereopsis, cognitive changes, perceived distance, voluntary effort, chromatic aberration, spherical aberration, astigmatism, and artists cues such as aerial perspective, overlap, linear

perspective, and shadows. These stimuli are all cues to the perception of distance and they might be used to guide accommodation or vergence or both systems.

Both blur and disparity drive neurological feedback control systems. These feedback pathways are independent of one another. Vergence is much more tightly controlled by its negative feedback than accommodation in that it tolerates smaller errors. The depth of focus for accommodation for an eye with a 3 mm pupil is approximately 0.4 D (Campbell 1957) whereas Panum's fusional range for equivalent targets is ±10 arc minutes (Ogle 1952) which corresponds to 0.01 D at 40 cm viewing distance.

Overview of this investigation

This investigation, using Schor's (Schor and Kotulak 1986) dual interaction model of accommodation and vergence sought to determine how three different stimuli, namely dynamic size changes, voluntary effort, and luminance changes might influence accommodation and vergence. The mutual independence of the accommodative convergence and convergence accommodation crosslinks are primary features of this model. The AC/A and CA/C ratios were used as a tool to determine whether changing size or voluntary effort was primarily influencing accommodation or vergence. Another main feature of this model is the separate tonic adapters for vergence and accommodation that occur after the

crosslinks. Schor et al. (1986) found that tonic aftereffects of accommodation are masked in darkness. We investigated the effect of different luminance levels on these tonic aftereffects.

In chapter 2, changing size was found to produce changes in both accommodation and vergence and these changes occur in a ratio like the AC/A ratio rather than the CA/C ratio. This indicates that changing size is stimulating accommodation primarily and vergence secondarily through the AC/A crosslink. Another finding was that changing size has a significant influence on accommodation and vergence when the changing size stimulus is combined with a changing blur or disparity stimulus. The results of the present study indicate that changing size is a significant stimulus to the oculomotor system and that the influence of changing size needs to be considered in studying the functions of accommodation and vergence in natural environments.

In chapter 3, voluntary effort is shown to produce changes in accommodation and vergence in proportions of an AC/A ratio rather than a CA/C ratio. Thus, voluntary effort is driving accommodation primarily and vergence secondarily through the AC/A crosslink. Voluntary effort may work through a mechanism which is similar to a trained or conditioned response of accommodation or vergence. In general, voluntary effort caused accommodation primarily and

vergence through an AC/A crosslink, but one subject could voluntarily accommodate without changing her vergence.

In chapter 4, accommodative aftereffects were shown to be masked in scotopic luminance levels and partially masked at mesopic luminance levels when the accommodative loop was opened with a pinhole. Thus, accommodative aftereffects may be more significant than studies using dark focus measures as the resting focus indicate.

Interactions of accommodation and vergence

The Maddox (1907) theory of vergence provided much of the original basis for clinical assessment of the vergence system. The simplicity of components described by Maddox and their suggested linear additivity enabled graphical analysis to develop. These components are: (1) tonic convergence; (2) accommodative convergence (AC), convergence caused by the effort of accommodation; (3) convergence due to "knowledge of nearness," now termed proximal vergence; (4) fusion convergence, now termed disparity vergence. This theory overlooked the complications of vergence accommodation and prism adaptation of vergence.

Fincham and Walton (1957) maintained that convergence accommodation was the process linking lens changes to the vergence system. They did not , however consider vergence accommodation and accommodative vergence to be separate.

Semmlow and Hung (1980, 1981) pointed out evidence in favor of a dual interaction theory with two independent interactive processes of vergence accommodation and accommodative vergence. Consequently, dual interaction theories for accommodation and vergence have been developed (Semmlow and Hung 1983). Schor and Kotulak's (1986) interactive model also includes controllers for adaptation of accommodation and vergence and will be the model that is primarily referred to throughout this thesis. With this dual interactive theory as a model, the various stimuli to accommodation and vergence can be examined along with the resulting interactions.

Heath (1956) pointed out that accommodation, like vergence, can similarly be grouped into four components: (1) Tonic accommodation; (2) convergence accommodation (CA), accommodation caused by the effort of vergence; (3) proximal accommodation; (4) reflex accommodation. The reflex accommodation is generally considered to be the adjustment of the lens to defocus blur.

If there are separate accommodative and vergence systems linked by independent crosslinks of vergence accommodation and accommodative vergence, then do the components of accommodation or vergence occur separately or do some components occur secondarily as a result of the crosslinks of vergence accommodation or accommodative vergence? For example, proximal accommodation and proximal

vergence might be two separate responses or one might be the result of the other due to a crosslink interaction. Both dynamically changing size and voluntary effort produce changes in vergence and accommodation. In chapters 2 and 3, changing size and voluntary effort were examined in terms of which controller, accommodation or vergence, was being stimulated primarily.

Dual interaction models of accommodation and vergence

The dual interaction theory provides a framework that may be experimentally verified. Semmlow (1981) reviews a number of experiments that are consistent with his dual interaction model (figure 1) and refute the Maddox hierarchy and Fincham model. With this model the blur that occurs on each side of the zone of single clear binocular vision, which is plotted in graphical analysis, is due to convergence accommodation. The independent crosslinks of his model are its most significant characteristics. This model only incorporates blur and disparity stimulation. Semmlow (1981) acknowledges "that proximal and voluntary components may contribute to the day to day operation of the near triad" but dismises them from use in experimentation because they are difficult to control in a quantitative manner. A dual interaction model has proven valuable as a guide to accommodation and vergence , so in chapter 2, I simultaneously examine the response of both accommodation

and vergence to changing size and from their relative amounts predict where these stimuli input into the model.

This interactive model can also serve as a valuable heuristic tool in understanding other aspects of accommodation and vergence. If the tonic bias levels occur after the crosslink, then accommodation and vergence would be expected to go to independent levels when accommodation and vergence are open loop and there is no stimulus present to accommodation and vergence. This has in fact been found clinically by several investigators (Fincham 1962, Bohman and Saladin 1980, Owens and Liebowitz 1980, Kotulak and Schor (1986). The frequently sought correlation between dark focus and dark vergence or relationships of AC/A or CA/C with these dark bias levels are not predicted from this model.

Schor (Schor 1979, Schor and Kotulak 1986) offers a dual interaction model (figure 2) in which tonic adapters for vergence and accommodation are included. This model is a good framework for understanding prism adaptation and adaptation of accommodation that affects the dark focus. In fact, predictions, made with the model as a guide, about adaptation and the interactive AC/A and CA/C crosslinks have been experimentally confirmed. Schor et al. (1986) found significant adaptation of accommodation that was present when the accommodative loop was opened with a pinhole pupil that was masked in darkness. With the model in mind, the

effect of luminance on this adaptation was investigated in chapter 4.

Dynamic changes in size

Kruger and Pola (1985) have shown shown that sinusoidal changes in size produce changes in accommodation. Erkelens and Regan (1986) have shown that sinusoidal changes in size produce changes in vergence. In addition, they found that when the stimulus combined size change with vergence change, vergence tracking was more accurate and less noisy than when the eyes were stimulated with the disparity component alone.

In chapter 2 the effect of dynamic sinusoidal size changes on accommodation and vergence are examined. A dual interactive system is assumed and the response of accommodation and vergence to size changes is compared to the response to blur and to disparity. This comparison was done to determine whether one controller, accommodation or vergence, was stimulated primarily or whether they were both stimulated.

Voluntary changes in accommodation and vergence

Subjects have been shown to be able to make voluntary changes in vergence and accommodation. Verhoeff (1947) mentions that he had good voluntary control of vergence and that in his younger days he could not separate vergence from accommodation in the absence of a stimulus. Despite

this control, he felt that vergence was a reflex in most situations. Fincham (1951) reported that the normal adjustment for near vision resulted from a voluntary effort initiated by the consciousness. Marg (1951), Malmstrom and Randle (1976), Cornsweet and Crane (1973), and others all reported voluntary control of accommodation. Voluntary accommodation was generally found to be associated with vergence in these studies. In chapter 3, voluntary changes in accommodation and vergence are examined by essentially the same technique that was used in looking at the effect of size looming. We sought to determine whether accommodation or vergence was being stimulated directly by size cues to distance.

Properties of AC/A and CA/C

It was felt that the response AC/A and CA/C ratios would be a direct way for examination of the question of whether size changes stimulated accommodation or vergence directly. While the response of accommodation to a blur stimulus may be variable, the response AC/A has been shown to be steady and the result of accommodative effort rather than accommodative stimulus (Alpern et al. 1959). Flom (1960a) studied the stability of the AC/A ratio and found the response AC/A to be quite stable (standard deviation .12 prism diopter/diopter).

Alpern et al. (1959) studied the linearity of the AC/A ratio and found a linear response over the central range of 1-5 D. Flom (1960b) also investigated the linearity of the AC/A and concluded that the nonlinearities he found were of no practical significance. Similarly, the CA/C is reported to be linear at intermediate levels of convergence (Morgan 1954, Kent 1958, Kersten and Legge 1982).

In the present investigation I examined accommodation in this middle range. The ranges of accommodation and vergence that were measured under different stimulus conditions were matched so that when comparisons were made, nonlinearities would cancel. Difference in AC/A and CA/C would therefore not be the result of measuring accommodation and vergence at different response levels.

The results of this study demonstrated that the AC/A and CA/C ratios are not related in a reciprocal manner. While Fincham's theory (Fincham and Walton 1957) of one interactive process predicts that AC/A and CA/C ratios are reciprocally related, the existence of two interactive components as demonstrated by Semmlow and Hung (1981), predicts differences. In fact Fincham himself reported the average CA/C ratio to be 1 D/MA for younger people (Fincham and Walton 1957) and the AC/A ratio to be .7 MA/D. Balsam and Fry (1959) also have reported that the AC/A and CA/C ratios are not reciprocally related.

Changing the AC/A

The AC/A is generally considered to difficult to alter by training (review in Borish 1976). Flom (1960c) reported that training only produced small changes in the AC/A. Schor and Tsuetaki (1987) and Tsuetaki (1986) transiently altered the AC/A and CA/C by fatiguing the tonic adapters. Miles and Judge (1982) affected the AC/A with a telestereoscope that optically widened or narrowed the pupillary distance with mirrors. By determining the affects of changing size, volition, and luminance on accommodation and vergence we hoped to better undertstand the interactions of accommodation and vergence. Our finding that voluntary accommodation causes changes in accommodation and vergence in a manner typical of the AC/A ratio may help explain why AC/A ratios are generally not altered by training.

Primary component in the near response

The Maddox hierarchy predicts that accommodation drives the vergence response through accommodative vergence and that fusional (disparity) vergence was used for fine adjustment. Fincham and Walton (1957), on the other hand, believed that disparity driven vergence dominated the near triad. Stark et al. (1980) pointed out that with even moderate disparities, the accommodative system would have no effective stimulus because the target would be off of the

fovea, and therefore disparity drives the initial or primary vergence response. The Hung and Semmlow (1981) model of the near response predicted that stimulus dominance depends on AC/A and CA/C ratios and that for most subjects, the accommodation and vergence responses are primaily driven by disparity.

These analyses of the primary component are based on blur and disparity as the stimuli to accommodation and vergence. In chapter 2, changing size is found to stimulate primarily accommodation rather than vergence. In chapter 3, voluntary effort is found to also be primarily stimulating accommodation. This implies that in an enriched natural environment, the analysis of which system is responding primarily will have to consider other stimuli to accommodation and vergence besides blur and disparity. Voluntary effort and changing size cues seem to be highly significant.

Perceived distance and accommodation and vergence

Accommodation and vergence can theoretically be used to determine distance. Descartes (1637/1965) in the 17th century, proposed that accommodation and vergence may determine the apparent distance of fixated objects. Boring (1942) and more recently Foley (1978) reviewed their role in the perception of distance. Accommodation is usually considered to be an ineffective cue, while vergence is

correlated with distance perception in low illumination (Owens and Liebowitz, 1980). Heineman, Tulving, and Nachmias (1959) reported that size changes of objects viewed under reduced conditions can be attributed to changes in vergence, and changes in accommodation are not necessary for changes in perceived size. Richards and Miller (1969) also reported that vergence may be a cue for distance perception. Vergence is believed to be a cue to distance because of a size-constancy relationship (review in Epstein 1977). In general, however, convergence is considered to be a weak cue to distance.

If vergence or accommodation influence perceived distance, then tonic levels of vergence and accommodation might be expected to bias perceived distance to some intermediate distance. This bias is in fact found under reduced stimulus conditions when there are no contextual cues to distance. Gogel (1969, Gogel and Tietz, 1973) reported this bias as a specific distance tendency. Owens and Liebowitz (1980) reported dark vergence to be correlated with perceived distance but not with dark focus. Correlation, however, does not prove causation and another explanation for this result would be that perceived distance determines the vergence. In fact, proximal vergence might be the basis for this correlation.

Perceived distance has been considered a stimulus to proximal vergence since Maddox (1907). The difference

between AC/A ratios determined by the gradient method and the multiple test distance method can be attributed to proximal vergence (Rubie 1979-80). Similarly, Ogle and Martins (1967) found a difference between near and far associated phorias that was attributed to proximal vergence. They even defined a P-C/A ratio, the amount of proximal convergence associated with each level of accommodative stimulus. Parks (1958), however believed that proximal convergence simply derived from proximal accommodation. Alpern (1958), Hofstetter (1942), and Morgan (1944) all found proximal vergence to be independent of accommodative convergence and associated with perceived distance. In a review, Morgan (1968) concluded that proximity is a stimulus for vergence independent of accommodative vergence. Erkelens and Regan's report (1986) of dynamic size changes of vergence might be explainable as a type of proximal vergence. In fact, their response of vergence to changing size showed several close correlations with motion-in-depth sensation.

Ittleson and Ames (1950) found evidence for proximal accommodation. Others, however, feel proximal accommodation is either small or nonexistant (Hofstetter 1942, Alpern 1958, Morgan 1968). Instrument myopia is often attributed to proximal factors (Bradford and Lawson 1954) though perhaps resting focus can explain most instrument myopia (Hennessy 1975). Ittleson (1960) in a review indicated that

there was more support for proximal vergence than proximal accommodation. Kruger and Pola (1985), reported that changing target size is a stimulus for accommodation. This stimulus is different from defocus blur and yet it caused a substantial response. The apparent distance may have been a factor in this response even though this result seems to be at odds with reports of small proximal accommodation effects.

The accommodative loop was closed in the previous studies that concluded that proximal convergence was independent of accommodative convergence. Therfore, blur driven accommodation would have inhibited any accommodative response to changes in perceived distance. Also, these studies did not consider the independent convergence accommodative crosslink and whether vergence was stimulating accommodation.

The previous studies of change in perceived distance involved static changes in distance. In chapter 2, dynamic sinusoidal changes in size and their effects on accommodation and vergence were examined. Dynamic changes in size invoke changes in perceived distance. Therefore, the looming stimulus may be related to proximal effects. Voluntary changes or training might also cause the accommodative and vergence response to looming size. In chapter 3, the response of accommodation and vergence to

voluntary changes was examined to determine if one of the two systems was being stimulated primarily.

The Maddox component model of vergence and accommodation basically ignores voluntary changes of accommodation and vergence. Visual imagery might be used to elicit proximal accommodation or proximal vergence. A number of investigators have reported the presence of voluntary accommodation (Marg 1951, Campbell and Westheimer 1960, Randle 1970, Cornsweet and Crane 1972). Most of these studies report an associated change in vergence along with the change in accommodation. Learning or training might allow accommodation and vergence to respond to stimuli other than the classic blur and disparity. The relative amplitudes of vergence and accommodation produced by voluntary efforts were determined in order to predict the location where voluntary effort was acting in a dual interactive model of accommodation and vergence.

A number of stimuli that are associated with the perception of depth have been shown to affect convergence and accommodation. Kruger and Pola (1986), Fincham (1951), and Campbell and Westheimer report that chromatic aberration can be a stimulus to accommodation. Size (Ittleson and Ames 1950) and changing size (Kruger and Pola 1985, Erkelens and Regan 1986) cause changes in both accommodation and vergence. Enright (1987) reported changes in vergence when viewing different locations in two dimensional pictures

containing perspective cues. In addition there are other factors which may influence oculomotor responses. These include spherical aberration, astigmatism, fluctuation of accommodation, and cognition (Fincham 1951, Alpern 1958, Campbell and Westheimer 1959, Kruger 1980).

Defocus blur is an even error cue to accommodation in that the blur does not indicate the sign of the accommodative error. Troelstra et al. (1964) classified clues that indicate the sign of a given error into: (1) target associated clues such as size or intensity or predictable stimulus presentation, and (2) eye associated sign cues such as astigmatism, chromatic, spherical and other aberrations, and small 2 c/s lens oscillations. One of their three subjects did not use eye associated clues. However other small clues, intentionally introduced resulted in 100 per cent correct responses. For focus errors of less than 1 diopter, Fincham (1951) found chromatic aberration to be used as a sign clue and Campbell and Westover (1959) found chromatic aberration, spherical aberration and astigmatism could act as sign clues.

Tonic levels of vergence and accommodation

In the dark, vergence and accommodation assume a dark focus and dark vergence level respectively. These levels have been found to be dissociated (Fincham 1962, Bohman and Saladin 1980) . This dissociation would be modeled as tonic

levels for both accommodation and vergence occurring after the AC/A and CA/C crosslinks. The dark accommodative level is equal to the empty field focus (Whiteside 1952). The dark focus may vary over 4 diopters between individuals, but the mean for a college population is about 1.5 diopters (Liebowitz and Owens 1978). Johnson, Post, and Tsuetaki (1984) reported a dark focus of 1.1 diopters. The eyes converge to an intermediate distance in the dark. Owens and Liebowitz (1976) reported an average distance of 116 cm.

Schor's model (Schor and Kotulak 1986) contains an obvious explanation for dissociation of vergence from accommodation in the dark. The vergence and and accommodative tonic controllers may show different levels of adaptation and have different rates of decay. Since both tonic controllers are beyond the AC/A and CA/C crosslinks, changes in tonic vergence or accommodation do not cause changes in the other system when both systems are open loop. This dissociation due to differences in adaptation of the controllers has been demonstrated by Kotulak and Schor (1986). Two other causes for dissociation would be: (1) random fluctuation in either vergence or accommodation after their points of crosscoupling or (2) some stimulus, such as a proximal or voluntary input to one of the systems beyond the point of crosslink interactions, that could occur in the dark.

Stability of the dark focus and dark vergence

Some studies have reported the dark focus to be quite stable (Miller 1978, Mershon and Amerson 1980). Mershon and Amerson found that the dark focus only varied .03 to 1 diopter over a period of several weeks. Other studies (Heath 1962, Baker et al. 1983, and Johnson et al. 1984) have observed significant variability of the resting level in the dark using infrared optometers. They report fluctuations of up to ±1.5 diopters over short periods of time. Baker et al. (1983) reported a 1 diopter zone of rest focus rather than a single position of rest focus.

The dark vergence position is generally reported to be more convergent than the light phoria position and at an intermediate distance ranging from 50 cm to a few meters. Its stability has not been carefully evaluated. Vergence seems more adaptable than accommodation and may be adapted independently of accommodation (Owens and Liebowitz 1980). Schor's report (Schor et al. 1986) that adaptation of accommodation is masked by darkness creates the question of whether dark focus is a measure of tonic adaptation.

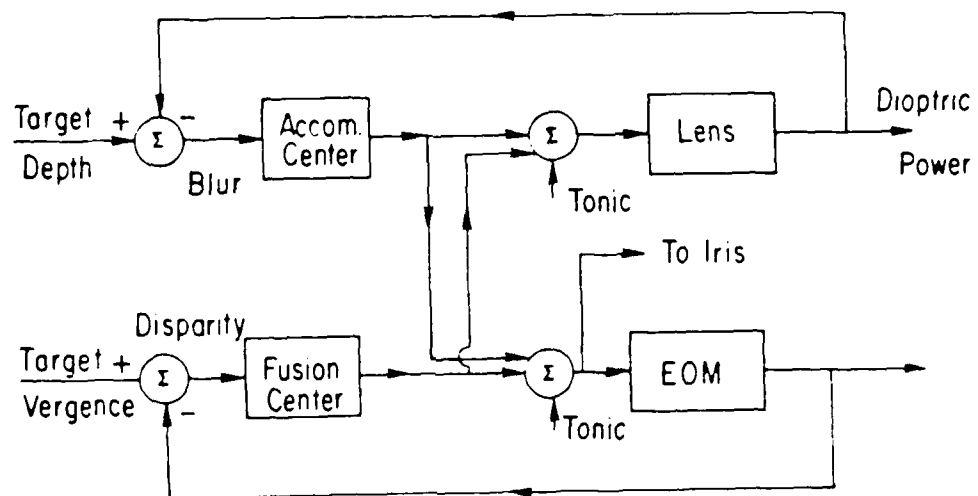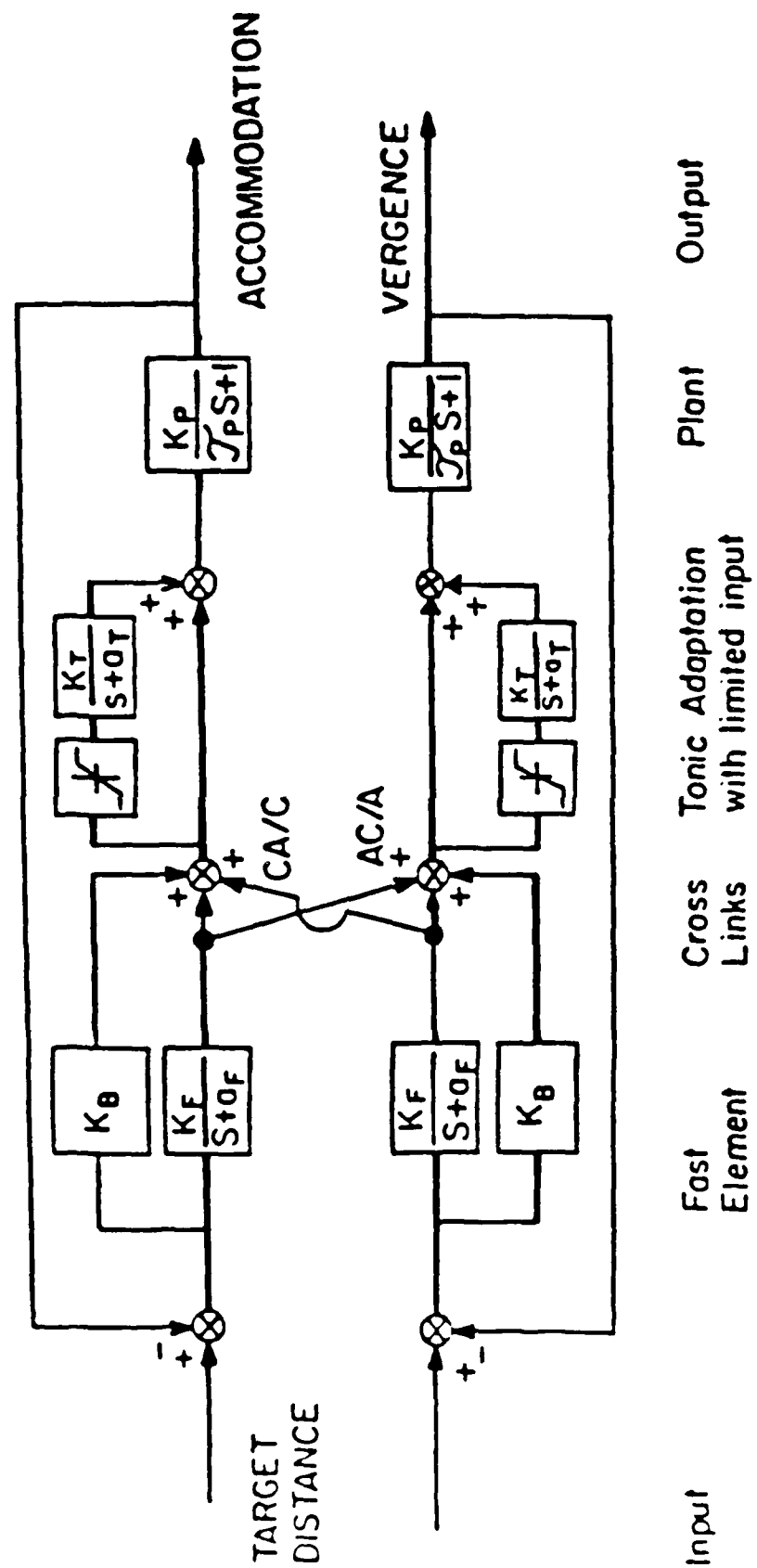Fig. 1. Semmlow's (1981) dual interaction model of accommodation and vergence.

Fig. 2. Schor and Kotulak's (1986) dual interaction model
of accommodation and vergence. Both accommodation and
vergence have phasic and tonic integrators.

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Chapter 2

Changing Size as a Stimulus to Accommodation and Vergence

A change in target distance causes the near response of pupillary change, accommodation, and vergence. Defocus blur is considered a major stimulus to accommodation (Phillips and Stark 1977) and disparity is a major stimulus to vergence (Stark et al. 1980). It is generally accepted that the accommodation and vergence system have dual interactions. Vergence causes accommodation through a CA/C crosslink and accommodation causes vergence through an AC/A crosslink. Proposed dual interaction theories (Semmlow and Heerema 1979, Schor 1979, Schor and Kotulak 1986, and Carroll 1982) neglect possible secondary stimuli such as size changes, brightness, interposition, chromatic aberration, perceived distance, and volition.

Ittleson and Ames (1950) have reported static changes in size to cause changes in accommodation due to changes in preceived distance. Alpern (1958) and Morgan (1968), failed to confirm this accommodative effect, but did find a proximal effect for vergence. The proximal vergence is apparently taking place without a concomitant change in accommodation. More recently, Kruger and Pola (1985), have found changes in accommodation with dynamic changes in size, and Erkelens and Regan (1986) have found changes in vergence

with dynamic changes in size. Therefore, there may be an interaction between accommodation and vergence when dynamically changing size is a stimulus to accommodation and vergence.

This study was undertaken to investigate several near response interactions, namely whether changing size was driving accommodation directly and vergence secondarily through an AC/A crosslink, whether changing size was driving vergence directly and accommodation secondarily through a CA/C crosslink, or if both accommodation and vergence were stimulated directly by changing size. AC/A and CA/C ratios were determined in order to exclude some of these possibilities. The vergence and accommodation systems were both made open loop by having the subject view the target monocularly through a pinhole. When viewing monocularly through a pinhole, the changes in accommodation and vergence are not modified by the feedback of blur or disparity.

We report that vergence and accommodation respond to sinusoidally changing size in a ratio characteristic of the response to blur, an AC/A ratio, rather than a CA/C ratio. In addition, we report that changing size has a significant impact when size and blur or size and disparity are simultaneously changed. We imply that changing size is primarily a stimulus to accommodation and secondarily a stimulus to vergence.

For ease in reference, the ratio of the response of vergence and accommodation to size alone as a stimulus will be referred to as a "size AC/A ratio" and the reciprocal ratio will be referred to as a "size CA/C ratio". The standard AC/A and CA/C ratios, determined with blur and disparity respectively, will be referred to as the "blur AC/A ratio" and "disparity CA/C ratio" respectively. Reference to the AC/A ratio or CA/C ratio without qualification will be to the ratios determined with blur alone and disparity alone as the stimulus. If changing size is combined with changing blur, the ratio will be referred to as the "blur + size AC/A ratio" and if changing size is combined with changing disparity, the ratio will be referred to as the "disparity + size CA/C ratio."

Methods:

Visual stimulus

The target was a Maltese cross (figure 1) produced on a
high resolution (640x480 pixel) video monitor. The cross
appeared as white on a dark background. The edges of the
cross formed angles of 36 degrees at the center. The cross
was sinusoidally varied in size by input from an IBM-AT
computer. The cross was varied from 38mm to 156mm in its
horizontal dimension. This was equivalent to a change in
visual angle from 3.25 to 13.1 degrees (4x change). When
the cross changed in size it mimicked a cross changing in
distance. It differed slightly from a real cross changing
distance because the screen pixels produced a finely
serrated edge that did not change in size as the cross
changed in size. These pixels subtended about 2.25 minutes.
Despite these edges the changing size of the cross did cause
the robust perception of a change in distance. The
experiments were run in a dark room so that the Maltese
cross target was the only visible target. The monitor
screen was placed at a distance 67 cm from points of the
apparatus that were conjugate to the subject's entrance
pupils for each eye.

Apparatus

An SRI binocular eye tracking system composed of a
fifth generation, two dimensional dual-Purkinge-image (DPI)
eyetracker and an infra-red optometer were used to
continuously track horizontal and vertical eye position and
accommodation (Crane and Steele 1978). The apparatus also
had a three dimensional visual stimulus reflector for each
eye that was used to change the stimulus to accommodation
and position of the target (Crane and Clark 1978). This
instrument has a resolution and noise level for eye position
of approximately 1 minute of arc and is essentially free of
the artifacts of head and eye translation. Its dynamic
infrared optometer measured accommodation to 0.1 diopter
(Crane and Steele 1978). This optometer measured
accommodation of the right eye. It is based on the Scheiner
principle (Randle 1970) and operates from a retinally
reflected infrared beam.

The three dimensional visual stimulus deflector allowed
movement of the stimulus object while its brightness and
visual angle remain fixed (Crane and Clark 1978). A pair of
lenses was used to make the target's image the object for a
telecentric Badal system (Fry 1969). Movement of one of
these lenses caused a change in the spherical power of the
system without a change in position, size, or brightness of
the image. This spherical power is linearly related to the

axial position in diopters. This lens could be moved by a servomotor controlled by the computer or by hand.

The same computer used to generate the visual stimulus and change its size was used to generate changes in blur by moving a lens of the visual stimulus deflector or to generate changes in absolute disparity by rotating a mirror galvanometer. Because the same computer was used to generate size, blur, and disparity, the phase and frequency for all stimuli were always equal. We could stimulate blur, disparity , and size alone or in any combination. The responses of accommodation and vergence along with the stimulus were continuously recorded on a strip chart. In order to reduce possible crosstalk of accommodative responses with eye position responses, the disparity stimulus was presented to only the left eye. This asymmetric stimulus also helped prevent eye movement from contaminating the accommodative response.

The accommodative loop could be opened by placing 0.5 mm pinhole pupils at points conjugate to the pupils of the eyes. With these pupils in place, our subjects would not detect or respond to ±3 diopters change in accommodative stimulus. Ripps et al. (1962) have shown that a reduction in pupil size can essentially eliminate the optical stimulus to accommodation for low levels of accommodative stimulus. Ward and Charman (1987) recently confirmed that a .5 mm pupil will produce open loop accommodation.

Procedures

The subjects were dilated with 2.5% phenylephrine hydrochloride, a weak sympathomimetic agent. One drop was instilled in each eye and another drop was added 5 minutes after the first. Phenylephrine does not change the resting focus (Garner et al. 1983) or the AC/A ratio (Sabin and Ogle 1958). The eyes were dilated so as to avoid pupil artifacts in the accommodative and eye position recordings. A headrest and mouthbite were also used so as to avoid artifacts.

To measure the AC/A ratio, the left eye was occluded and the subject viewed a stationary Maltese cross through a 4 mm artificial pupil. The pupil size was therefore effectively constant even though accommodation changed because the phenylephrine kept the pupil size above 4 mm. The computer was used to drive the optometer so that defocus blur (approximately 0.67 to 2.25 diopters) was produced sinusoidally. A response "blur AC/A ratio" was determined by dividing the change in vergence by the change in accommodation.

To measure the CA/C ratio, both eyes viewed the cross through pinhole pupils. The computer was used to rotate the mirror in a sinusoidal manner to produce asymmetric changes in disparity (about 5 prism diopters or 2.8 degrees). A response "disparity CA/C ratio" was determined from the change in accommodation divided by the change in vergence.

"Size AC/A ratios" and "size CA/C ratios" were calculated from the responses of vergence and accommodation to size changes without blur or disparity changes. For changing size alone as the stimulus, the subject viewed the cross monocularly through a pinhole. Under these conditions accommodation and vergence were both effectively open loop and were free to vary independent of feedback.

In addition to presenting single stimuli of changing size, blur, or disparity, we also combined the changing size with a changing blur stimulus and changing size with a changing disparity stimulus. For a changing blur plus size stimulus, the target increased and decreased in size simultaneously with the stimulus to accommodation. Similarly, for a changing disparity plus size stimulus, the target increased and decreased in size as crossed disparity increased and decreased. From these conditions we calculated a changing "blur + size AC/A ratio" and a changing "disparity + size CA/C ratio."

At the start of each experimental session, the eye movement recorder was calibrated by having the subject fixate 5 vertical line targets spaced horizontally at 2 prism diopter intervals while horizontal eye movements were recorded. Accommodation was initially calibrated with 0.5 diopter step changes of refractive error simulated with an artificial eye.

An experimental session consisted of measurements of accommodation and vergence responses to stimuli of sinusoidally changing size, changing disparity, changing blur, and combinations of blur and size and disparity and size. The order of presentations was pseudorandom and .05, .2, and .5 Hz stimuli were presented to each subject. Temporal square wave presentations of all stimulus combinations were also utilized on 4 subjects. The blur stimulus was presented for at least 5 cycles (3 cycles at .05 Hz and below) and then the blur plus size stimulus was presented. This was then repeated. The order was alternated in this way so as to directly compare one with the other so that instrument calibration and order effects would not bias the analysis. Similarly, this alteration of single stimuli and combined stimuli was done for comparing "disparity CA/C ratio" and "disparity + size CA/C ratio."

Three of the subjects were evaluated at 7 frequencies (.025, .05, .1, .2, .5, .67, and 1 Hz). In these three subjects the phases and amplitudes of motor responses were evaluated in order to determine frequency plots for amplitude and phase. For these evaluations, frequencies were randomized, and all frequencies for a given stimulus condition were presented in the same experimental session. An experimental session lasted up to 90 minutes. The subjects were instructed to always view the center of the cross and keep it clear and single.

Data analysis

The strip chart recordings of vergence and
accommodation were used to determine the AC/A and CA/C
ratios for the different stimulus conditions by measuring
the peak to trough changes of accommodation and vergence and
then calculating the ratio. The measurements were done
using a Houston instruments Hipad digitizer with a magnified
cursor. This digitizer has a resolution of .125 mm
(corresponding to .008 D and 1.25 arc min) so precise
measurements of the strip chart recordings could easily be
made. Phase of the accommodative and vergence motor
responses relative to the phase of the stimulus were
determined from the temporal phase lag (degrees) of the
peaks and troughs of the responses from the peaks and
troughs of the stimuli. Time resolution was 25 msec. This
method was essentially the same as used by Kruger (1986).
Ten or more cycles were analyzed except at .025 and .05 Hz
where 3 and 5 cycles respectively were analyzed.

The logarithms of the AC/A ratios and CA/C ratios were
averaged so that after averaging, the "size AC/A ratio"
would be the reciprocal of the "size CA/C ratio." The
response of convergence to a blur stimulus depends on the
response of accommodation to the stimulus (Alpern 1959).
The AC/A and CA/C are effectively the gains of the cross
coupling interactions between the accommodative and vergence

systems. Using logs prevented low values of AC/A and CA/C from skewing the average results.

Subjects

Seven subjects took part in the experiment. They ranged in age from 19 to 38. They were accepted as subjects if the eye tracker was able to consistently lock onto them on an initial trial run. Six of the seven were naive as to the purpose of the experiment. They all were correctable to at least 20/20 acuity in each eye, and had normal stereopsis (20 arc sec) and normal amplitudes of accommodation for their ages. Refractive errors were corrected by adjustment of the stimulus deflector or by adding lenses to the stimulus deflector at the start of each experimental run. One subject was a low hyperope, 3 were emmetropes, and 3 were myopes.

Results:

"Blur AC/A ratio" compared to "size AC/A ratio"

The "blur AC/A ratio" was found to be quite similar to the "size AC/A ratio." The "size AC/A ratio" and "blur AC/A ratio" were plotted against each other in figure 2. Three sinusoidal frequencies (.05, .2, .5) are plotted for each subject. The dashed line is the 1:1 line. The points tend to lie along this line and the correlation is strong ($r = .9338$, $p<.0001$). This correlation suggests that the "size AC/A ratio" is similar to the "blur AC/A ratio."

In order to examine whether the "size AC/A ratio" is significantly different from the "blur AC/A ratio" a "within subjects AxBxS" analysis as described by Keppel (1982) was performed. The "size AC/A ratio" was not significantly different from the "blur AC/A ratio" ($F_{1,6}=3.74$, $p>.1$). There was no interaction between the frequency and the stimulus condition ($F_{2,12}=2.25$, $p=.15$). Figure 3 graphs "blur AC/A ratio" and "size AC/A ratio" for the averages across the 7 subjects at frequencies of .05, .2 and .5 Hz. Clearly, the averaged AC/A ratios for these subjects was consistent across stimulus temporal frequency.

"Disparity CA/C ratio" compared to "Size CA/C ratio"

The "disparity CA/C ratio" was found to be significantly different than the "size CA/C ratio." Figure

4 shows a plot analogous to figure 2 but for "size CA/C ratio" and "disparity CA/C ratio." The points are much more scattered than in figure 2 and the correlation is much weaker (r=.5086, p=.0186). A similar within subjects analysis was performed for the averages of the seven subjects at each of the three frequencies. The "size CA/C ratio" was significantly different from the "disparity CA/C ratio" ($F_{1,6}$=16.14, p<.01). Figure 5 plots the 2 ratios as a function of temporal frequency. As with AC/A ratio, the CA/C ratio also varied little with temporal frequency. The results in figure 5 demonstrate that a changing disparity stimulus evokes accommodation and vergence in different relative amounts than a changing size stimulus. There is some interaction between frequency and stimulus condition ($F_{2,12}$=5.57, p=.0194).

"Blur AC/A ratio" compared to "Size + blur AC/A ratio"

The "blur AC/A ratio" was compared to the "size + blur AC/A ratio" to see if the response changed when changing size was added to changing blur. Figure 6 plots the averages for the 7 subjects at 3 frequencies for the two conditions. The "blur AC/A ratio" is not significantly different from the "size + blur AC/A ratio" ($F_{1,6}$<.01, p=.99)

"Disparity CA/C ratio" compared to "size + disparity CA/C ratio"

In contrast to the "blur AC/A ratio" vs. the "blur + size AC/A ratio" the "disparity CA/C ratio" was significantly different from the "disparity + size CA/C ratio" ($F_{1,6}=6.18$, $p<.05$). The "disparity CA/C ratio" and "disparity + size CA/C ratio" are plotted in figure 7. These lines are close together but they are significantly different at the .05 level. Interestingly, 6 of the 7 subjects showed a small increase in CA/C ratio when size was added to disparity.

Frequency plots for phase, amplitude, AC/A, and CA/C

Three of the subjects were examined at seven frequencies for each of the stimulus conditions. Examination of the phase and amplitudes and AC/A ratios and CA/C ratios in figures 8 to 16 reveals some general dissimilarities among the different stimulus conditions. This examination also reveals the variability among the three subjects for each stimulus condition.

Phase

Figures 8 to 12 show phase and amplitude responses for 5 different stimulus conditions. These conditions are size alone (figure 8), blur alone (figure 9), disparity alone (figure 10), size plus blur (figure 11), and size plus

disparity (figure 12). While the results for the averaged

subjects reported above indicated that the "size AC/A ratio"

is like the "blur AC/A ratio" in magnitude, it is obvious

that in all three subjects that the phase of the response of

vergence and accommodation is different for a blur stimulus

compared to a changing size stimulus (figures 8 and 9). For

the changing size stimulus, there is a small phase lead at

the lower frequencies and only a relatively small phase lag

at the higher frequencies (figures 8). Blur as a stimulus,

on the other hand, results in accommodation and vergence

lagging at all frequencies and there is a dramatic increase

in phase lag to over 200 degrees as frequency is increased

to 1 Hz (figure 9). With changing disparity as a stimulus,

there is a phase lag of only a few degrees at low

frequencies and only a small increase to about 50 degrees at

higher frequencies (figure 10). Generally, accommodation

and vergence under all stimulus conditions have very similar

phase lags or leads relative to the stimulus. When changing

size is added to either blur (figure 11) or disparity

(figure 12) the phase lag is decreased relative to the

single stimulus of blur or disparity. Changing size

therefore, is an important component of the stimulus that

significantly influences the phase lag of the response

(Kruger and Pola 1985).

Amplitude

For a changing size stimulus, the amplitudes of accommodation and vergence show variability from subject to subject (figure 8). Responses for accommodation range from about .1 diopter to over 1.5 diopters and vergence ranges from .05 meter angles (.33 prism diopters) to 2.4 meter angles (15 prism diopters). For changing blur, the responses of accommodation are largest at low frequencies and decrease at higher frequencies (figure 9). Similarly, for changing disparity, the responses of vergence are largest at low frequencies and decrease at higher frequencies (figure 10).

The open loop accommodative response tends to increase when changing size is added to a changing disparity stimulus, and thus the CA/C ratio appears to increase with size and disparity as a stimulus. In general, the accommodative and vergence responses with size added to disparity or blur tend to be more accurate and sinusoidal than responses to blur or disparity alone. This is in agreement with Erkelens and Regan (1986) that the vergence response to disparity and size combined is more accurate than the response to disparity alone.

AC/A ratios and CA/C ratios

There is substantial variability in AC/A ratios and CA/C ratios among subjects.

When looking at these three individual subjects, there is some variability between the "size AC/A ratio" and "blur AC/A ratio" (figure 13). The "size AC/A ratio" is consistently higher than the "blur AC/A ratio." However, for subjects DH and LS the "size AC/A ratio" and "blur AC/A ratio" are more alike than the "size CA/C ratio" and "disparity CA/C ratio" (figure 15).

Figure 14 plots the "blur AC/A ratio" and the "blur + size AC/A ratio" for three subjects. The lines are very similar. A simple explanation to account for no difference between these two lines is that changing size causes accommodation and vergence to respond in an AC/A ratio.

Figure 15 plots the "disparity CA/C ratio" and the "size CA/C ratio" for three subjects. For subjects DH and LS, the "size CA/C ratio" is markedly and consistently higher than the "disparity CA/C ratio." Subject PK is different in that the lines do not appear to be significantly different. DH and LS have responses which are consistent with the averaged results of the 7 subjects at three frequencies shown in figure 4.

Figure 16 plots the "disparity CA/C ratio" and the "disparity + size CA/C ratio" for three subjects. The "disparity + size CA/C ratio" is consistently higher than the "disparity CA/C ratio" for LS and DH. PK is again the exception and the "disparity + size CA/C ratio" is more

similar to the "disparity CA/C ratio."   If changing size
does not cause accommodation and vergence to respond in a
CA/C ratio, but rather in an AC/A ratio because
accommodation has been stimulated directly, then differences
between the "disparity CA/C ratio" and the "disparity + size
CA/C ratio" would be expected.

Step responses

Accommodative and vergence responses to step changes in
size of the cross, were examined in 4 of the subjects. The
response was qualitatively more similar to the AC/A ratio
than the CA/C ratio. However the responses to step stimuli
were variable and sometimes a ratio could not be measured.

Discussion:

Comparison of vergence responses to looming with the accommodative loop opened and closed

Erkelens and Regan (1986) reported changes in vergence to changing size. Our vergence responses were generally several times larger than the 10 or 15 minute responses reported by Erkelens and Regan. We believe the difference is because Erkelens and Regan had their subjects viewing size changes through natural pupils rather than a pinhole. If our subjects viewed the looming cross binocularly through natural pupils rather than pinholes, the response of vergence to changing size was greatly reduced. In addition, the vergence response decreased at lower frequencies, just as Erkelens and Regan reported. However, with a pinhole pupil, the vergence response did not drop at lower frequencies. The feedback of accommodation appears to be limiting the response of accommodation and subsequently vergence when viewing is done with natural pupils. This interpretation suggests that the vergence response to looming is associated with accommodative vergence, and that accommodation is the primary response to looming.

Kruger and Pola (1985) found accommodative responses to changing size of about 1 to 2 diopters. With accommodation of this magnitude, the associated vergence would be expected to be much larger than the 15 minutes of arc that Erkelens

and Regan found. Kruger's accommodative responses to size

changes were generally larger than the .25 to 1.5 diopter

responses of our subjects which would correspond to .5 to 3

degrees of accommodative vergence, assuming a normal AC/A of

2 degrees per diopter. Indeed, the open loop responses of

vergence to looming were in this range when a pinhole was

worn before the viewing eye.

Interactions between size, blur, and disparity stimuli to accommodation and vergence

Semmlow and Hung (1980, 1981) have made the point that

vergence accommodation is a significant and perhaps primary

component in the near response under binocular conditions.

In a natural viewing condition, in which size change

accompanies disparity and blur changes, the changing size is

an additional component that must be considered. Both

Kruger and Pola (1985) and Erkelens and Regan (1986) found

that adding changing size to blur and disparity respectively

increased the response amplitude accuracy. My responses

were also more accurate because the phase lag of vergence

and accommodation was reduced when size was added to

disparity or blur. In a typical environment, changes in

disparity and blur are accompanied by changes in size, and

when targets are viewed binocularly, the accomodative

response may be significantly influenced by the change in

size.

Possible explanations for the phase of accommodative and vergence responses

One explanation for the phase lead at the lower frequencies for vergence and accommodation is that the accommodation is responding to the rate of change of target size. The rate of change of target size for a sinusoidal stimulus leads the phase of the stimulus by 90 degrees. However the lead at most is only 20 or 30 degrees ahead of the stimulus. If the lead is reduced by a constant time delay or latency of 400 msec, the phase lead is smaller than predicted for a velocity sensitive response.

Another explanation for the phase lead is that there is a predictor operator for changing size and that changing size is more predictable than is changing blur or disparity. These targets were regular and predictable and perhaps accommodation or vergence can respond to changing size better than blur or disparity. Krishnan et al. (1973) report predictor operators in the triadic system with small effects. Erkelens and Regan (1986) did not find evidence for a predictor operator for disparity stimuli, but such an operator might explain our phase responses to changing size, and the reduction in phase lag when changing size is added to changing disparity or changing blur.

Voluntary type changes might also explain the phase lead of the response to changing size. Voluntary effort may result from anticipation by the subject of the size changes.

While instructions to the subjects were to fixate the center
of the cross and keep it clear and single, it is possible
that subjects may be more prone to respond voluntarily to
changing size than to changing blur or changing disparity.
In the next chapter, the effect of voluntary effort on
vergence and accommodation will be examined.

Changing size and perceived distance

Most of the subjects reported that the cross appeared
to be moving toward and away from them as the cross changed
size. But changing disparity or changing accommodation
alone did not produce such a change in perceptual distance.
The change in perceptual distance may have produced a change
in proximal vergence. Proximal vergence has been reported
since Maddox (Morgan 1968, Ogle and Martens 1957). It is
unclear whether proximal vergence produces an accommodative
change through the CA/C crosslink. A small proximal effect
may be present in my results but the accommodative response
and accommodative vergence seems to be the primary system
stimulated.

Ittleson and Ames (1950) reported proximal
accommodation and vergence. However, Hoffstetter (1950)
pointed out that the proximal vergence responses that
Ittleson and Ames reported were explainable by accommodative
convergence. Our results might be explained as
accommodation responding to perceived distance changes and

accommodative vergence responding secondarily. We observed similar types of responses to a target dynamically changing in size as Ittleson and Ames observed for static targets of different sizes presented at different distances. Our responses were larger than theirs because we had the accommodative loops open with pinhole pupils. Also, we may have elicited different response amplitudes of accommodation than they found because static displays may not elicit as strong a response as dynamic changes in size.

Chromatic aberrations and texture cues to accommodation

Even when we opened the accommodative loop with a pinhole and the vergence loop by occlusion of one eye we have not removed all the secondary cues to accommodation and vergence. Chromatic aberration did not change with target size. Chromatic aberration is a stimulus to accommodation for some subjects (Fincham 1951, Kruger and Pola 1986). The static chromatic aberration cue that accommpanied dynamic size changes may have been limiting the accommodative response. Also, the fine serrations on the edge of the cross did not change in size and this was a cue that may also have decreased accommodation and vergence responses.

Apparently, the fine serrations on the edge of the cross did not detract from the perception of change in distance or the responses of accommodation and vergence. Four people were checked with the cross of this experiment

and with a projected cross with smooth sides. This cross was made on a 35 mm slide and its size was altered manually by a diaphragm. Both crosses produced qualitatively similar changes in vergence and accommodation. The subjects also reported similar perceptions of changing distance.

A model of looming responses of accommodation and vergence

Figure 17 is Schor's (Schor and Kotulak 1986) model of accommodation and vergence and includes separate crosslinks for AC/A and CA/C between vergence and accommodation. Since we have shown that changing size produces changes in accommodation and vergence, we sought to determine where the changing size is feeding into the accommodative and vergence systems. There are quite a few possibilities. Changing size could be feeding into both accommodative and vergence sides or into just one side. Also, changing size could be feeding into the system either before or after the crosslink to the other system. It is also possible that changing size influences accommodation and vergence via an entirely different process than is illustrated by the model.

One of the simplest possibilities is that changing size feeds into just one system, accommodation or vergence. If it feeds into just one system before the crosslink, then vergence and accommodation should occur in either a CA/C ratio or AC/A ratio respectively. If changing size feeds

into only one motor system after the crosslink, then only vergence or accommodation should respond but not both.

We found that both accommodation and vergence respond to changing size in a ratio equal to the AC/A ratio but not the CA/C ratio. This implies that accommodation is responding directly to changing size and that vergence is responding indirectly through an AC/A crosslink.

Nonlinearities in the AC/A and CA/C ratios would not be expected to be a problem in our determination of where the changing size stimulus inputs into the model. Stimulus ranges of size, blur and disparity were chosen to yield linear ranges for both the AC/A and CA/C. Alpern et al. (1959) has shown good linearity for the response AC/A ratio at intermediate stimulus values. Kersten and Legge (1983) have shown linearity for the CA/C ratio.

If Schor's model is used as a guide, the response of accommodation and vergence to a combined stimulus can also be used to predict the location of the input to the accommodative and vergence systems from changing size. If changing size is increasing accommodation before the AC/A crosslink, the AC/A ratio will be the same when blur is the stimulus as when changing blur plus changing size is the stimulus . If however, the stimulus of changing size is added to the vergence system before the CA/C crosslink, then the apparent AC/A ratio for a changing size plus blur stimulus will be different from the AC/A ratio stimulated

solely by changing blur. This difference would occur because the accommodative feedback loop is closed during accommodative vergence. If accommodation is changed by si...stimulation of the CA/C crosslink, feedback will change th...amount of optical reflex accommodation produced by the blu...stimulus. Whether the input to accommodation across the CA/C crosslink increases or decreases optical reflex accommodation depends on the sign of this vergence accommodation (increase or decrease) relative to the accommodation occuring from blur. In any case, except if the AC/A and CA/C ratio are reciprocally related, input to accommodation across the CA/C crosslink will cause a change in the "size + blur AC/A ratio" compared to the "blur AC/A ratio." By similar reasoning, if changing size is increasing vergence before the CA/C crosslink, the "disparity CA/C ratio" should be the same as the "size + disparity CA/C ratio" and if changing size is increasing accommodation before the AC/A crosslink then the "disparity CA/C ratio" should be different than the "size + disparity CA/C ratio."

We found that the "size + blur AC/A ratio" is not significantly different from the "blur AC/A ratio" while the "size + disparity CA/C ratio" is different from the "disparity CA/C ratio." These results are consistent with the changing size producing a change in accommodation prior to the site of the AC/A crosslink. Subject PK was an

exception to these interpretations. Size changes for PK
caused a response of accommodation and vergence in a ratio
that was more like the CA/C ratio than the AC/A ratio. It
is possible that there are differences between subjects and
that some respond in a CA/C ratio to changing size rather
than an AC/A ratio.

Subject LS in figure 15 is an interesting case. Her
CA/C ratio drops at low frequencies. Schor and Kotulak
(1986) reported this drop in CA/C ratio at low temporal
frequencies as a result of adaptable tonic vergence. The
"size + disparity CA/C ratio" did not drop as much at the
low frequencies. This would be consistent with changing
size causing an increase in accommodation directly.

Conclusions

Changing size (looming) stimulates accommodation
directly and vergence secondarily through an AC/A crosslink.
In addition, when changing size is combined with changing
blur or changing disparity, the phase lag of accommodation
and vergence are reduced and the response is more accurate.
Changing size is a significant stimulus in a natural
environment and it should be included in models of the
oculomotor system.

Fig. 1. Maltese Cross that was the target viewed by the subjects. It was white on a black background and was the only object visible to the subjects.
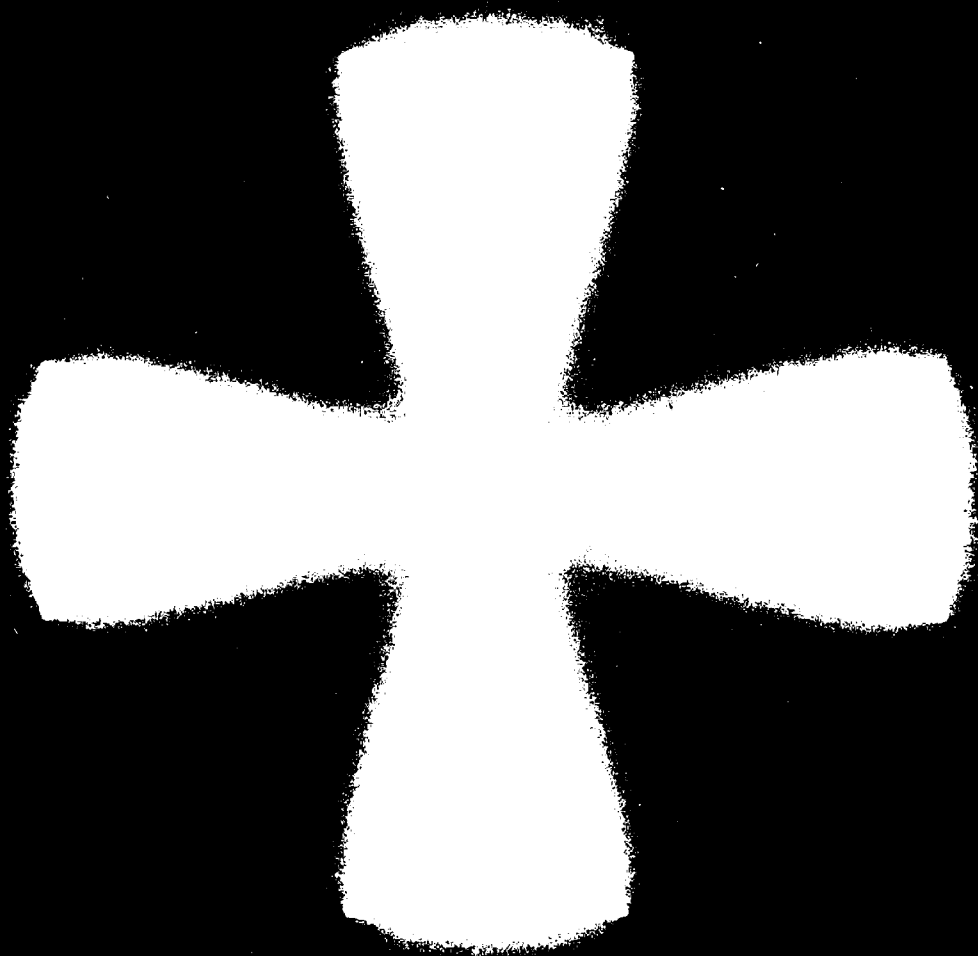
Fig. 2. Correlation of "size AC/A ratio" with "blur AC/A ratio." These are the results for 7 subjects to .05 Hz, .2 Hz, and .5 Hz sinusoidally changing stimuli. The response ratio of vergence to accommodation with changing size as a stimulus was similar to the response AC/A ratio to blur. The correlation is 0.9338. The dashed line is the 1:1 line. AC/A ratios are expressed as meter angles per diopter.
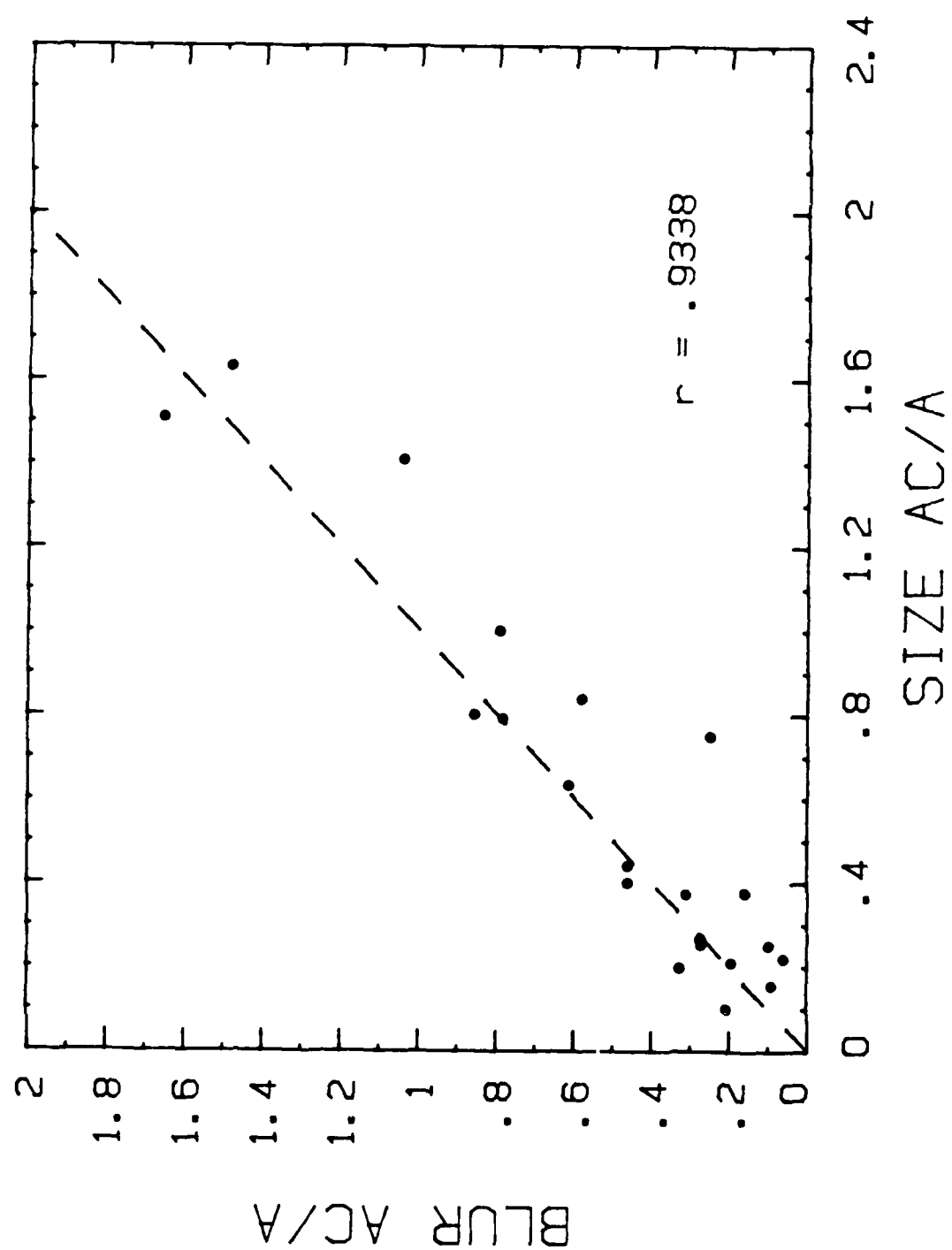
Fig. 3. "Size AC/A ratio" compared to "blur AC/A ratio."
Results for averages of 7 subjects at 3 frequencies. A
within subjects statistical analysis shows no significant
difference (p>.1). AC/A ratios are expressed as meter
angles per diopter.

RESPONSE AC/A

FREQUENCY (Hz)

BLUR
SIZE
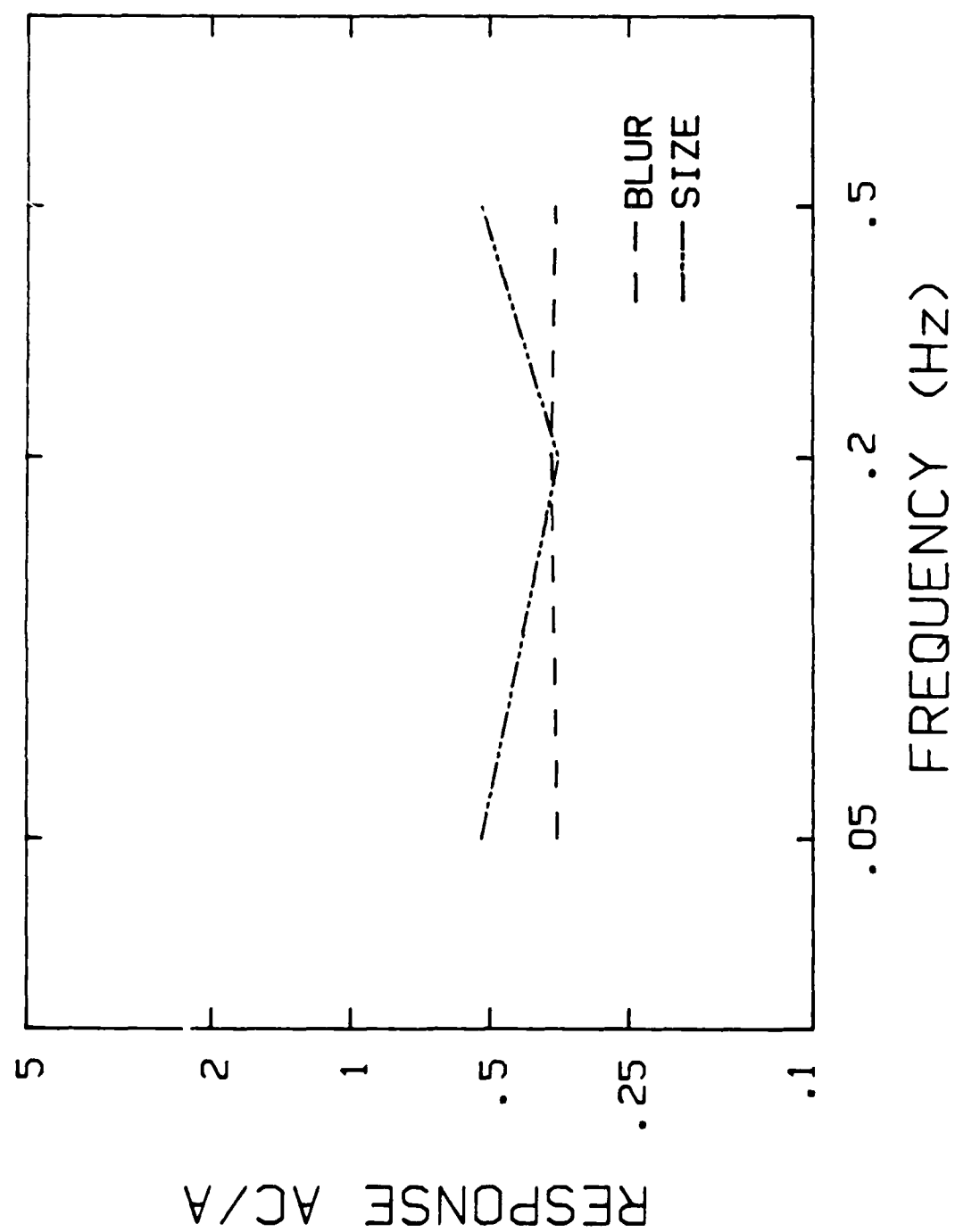
Fig. 4. Correlation of "size CA/C ratio" with "disparity CA/C ratio." These are the results for 7 subjects to .05 Hz, .2 Hz, and .5 Hz sinusoidally changing stimuli. The response ratio of accommodation to vergence with changing size as a stimulus was not strongly correlated with the response CA/C ratio to disparity. The correlation is 0.5086. There is much more variation of the "size CA/C ratio" compared to the "disparity CA/C ratio" than the "size AC/A ratio" compared to the "blur AC/A ratio." The dashed line is the 1:1 line. CA/C ratios are expressed as diopters per meter angle.
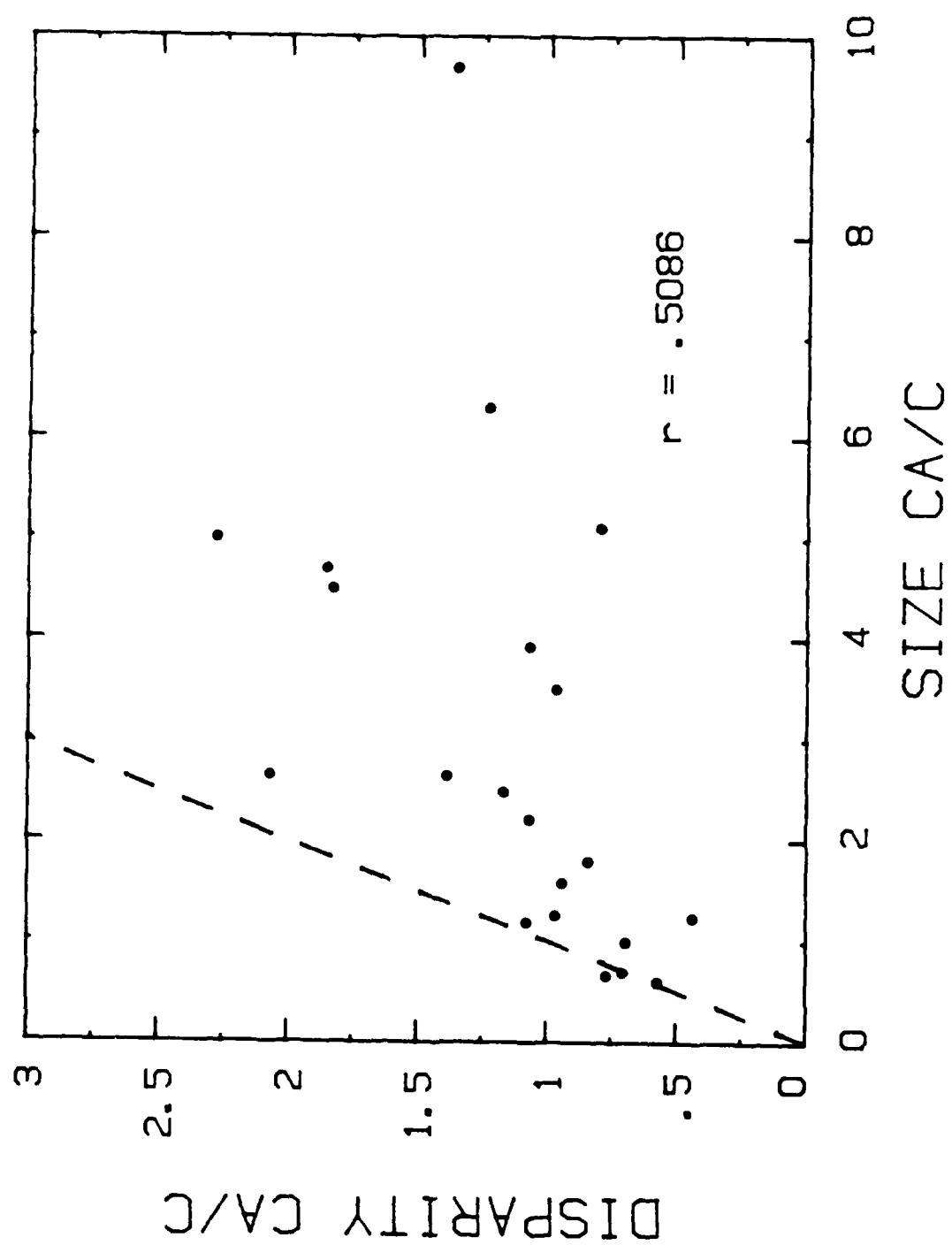
Fig. 5. "Size CA/C ratio" compared to "disparity CA/C ratio." Results for averages of 7 subjects at 3 frequencies. A within subjects statistical analysis shows a significant difference (p<.001). CA/C ratios are expressed as diopters per meter angle.
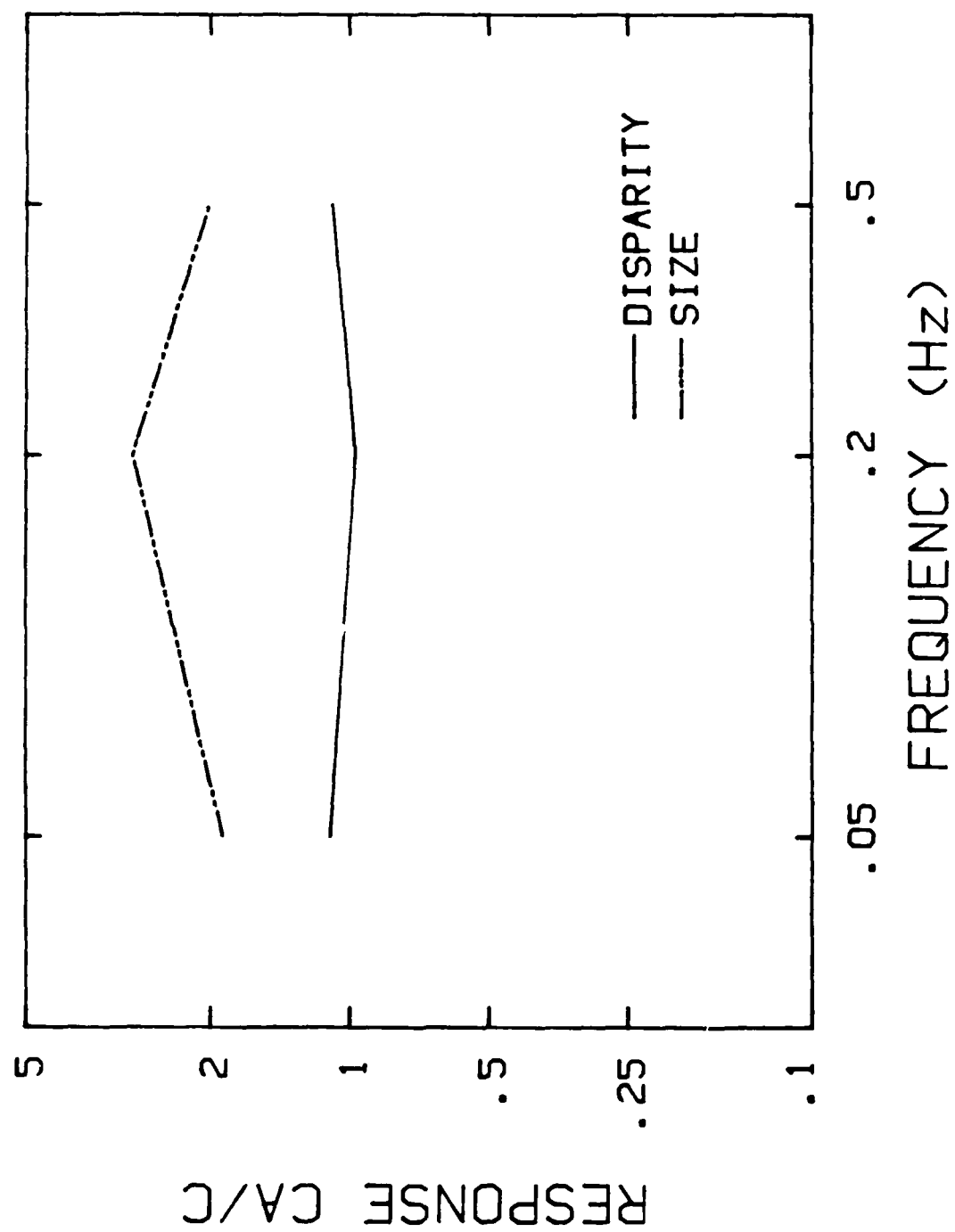
Fig. 6. "Blur + Size AC/A ratio" compared to "blur AC/A
ratio." Results for averages of 7 subjects at 3
frequencies. A within subjects statistical analysis shows
no significant difference (p>.1). AC/A ratios are expressed
as meter angles per diopter.
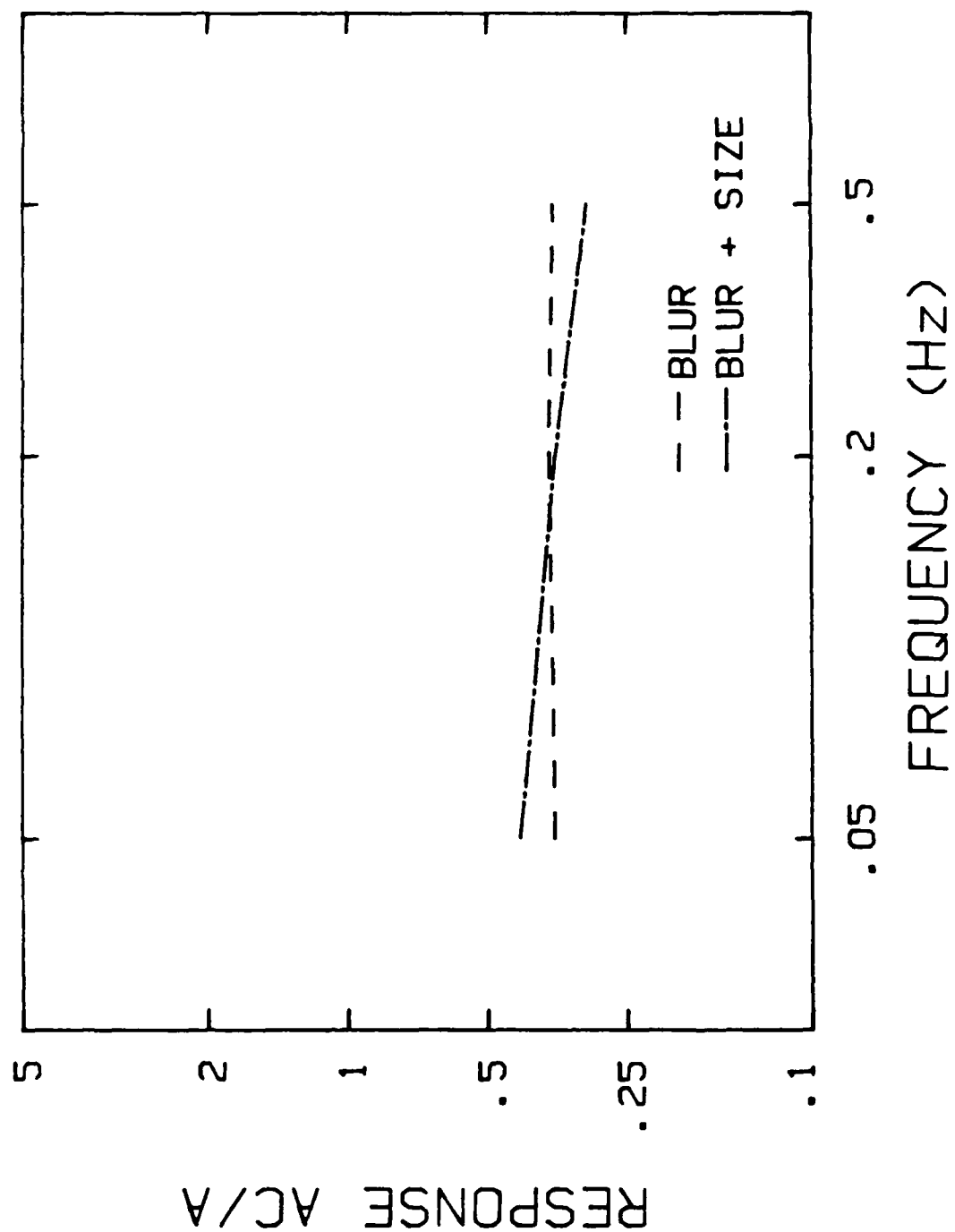
Fig. 7. "Disparity + Size CA/C ratio" compared to
"disparity CA/C ratio." Results for averages of 7 subjects
at 3 frequencies. A within subjects statistical analysis
shows a significant difference (p<.05). CA/C ratios are,
expressed as diopters per meter angle.

FREQUENCY (Hz)

RESPONSE CA/C

——DISPARITY
——DISPARITY + SIZE
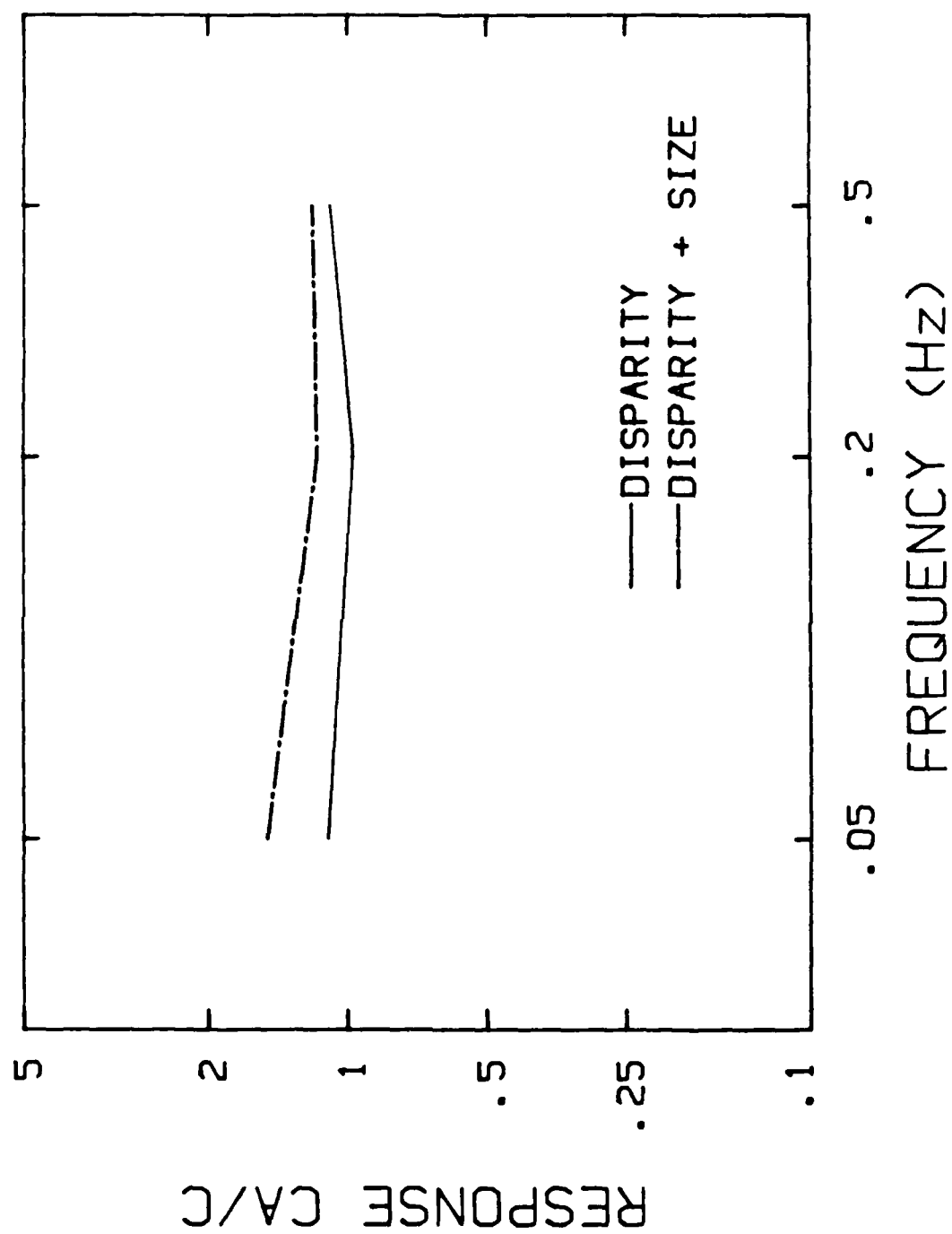
Fig. 8. Plots, for three subjects, of response amplitudes and phase of accommodation and vergence vs. frequency of stimulus. The stimulus is sinusoidally changing size (4x). The amplitude of vergence is measured in meter angles and the amplitude of accommodation is measured in diopters. The phase of accommodation and vergence are plotted relative to the phase of the changing size stimulus.
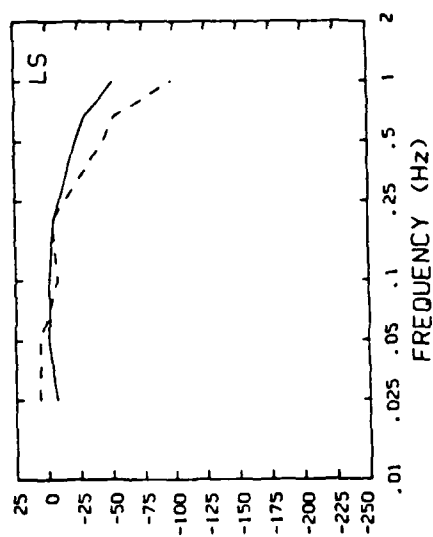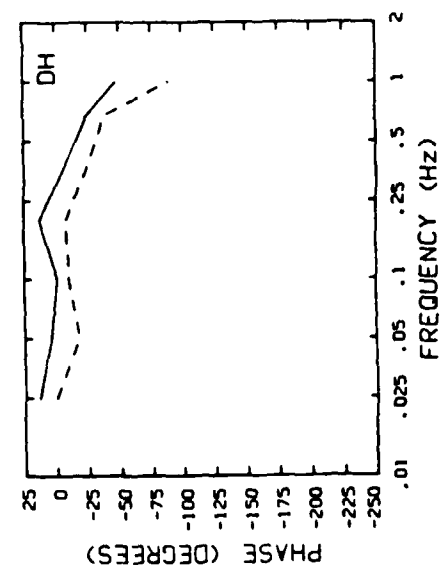
SIZE AS STIMULUS

72
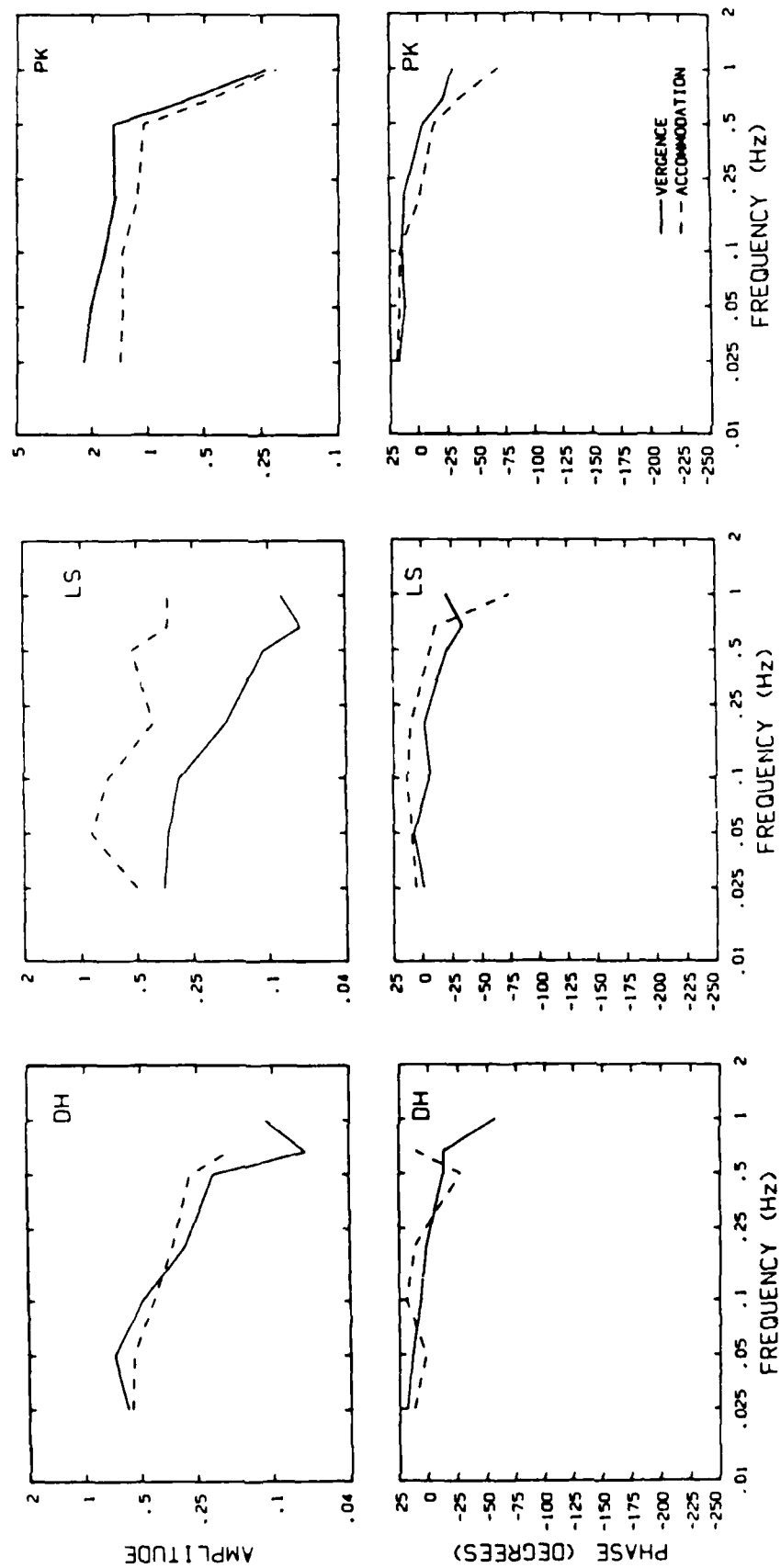
Fig. 9. Plots, for three subjects, of response amplitudes
and phase of accommodation and vergence vs. frequency of
stimulus. The stimulus is changing blur of 1.67 diopters.
The amplitude of vergence is measured in meter angles and
the amplitude of accommodation is measured in diopters. The
phase of accommodation and vergence are plotted relative to
the phase of the changing blur stimulus.

BLUR AS STIMULUS
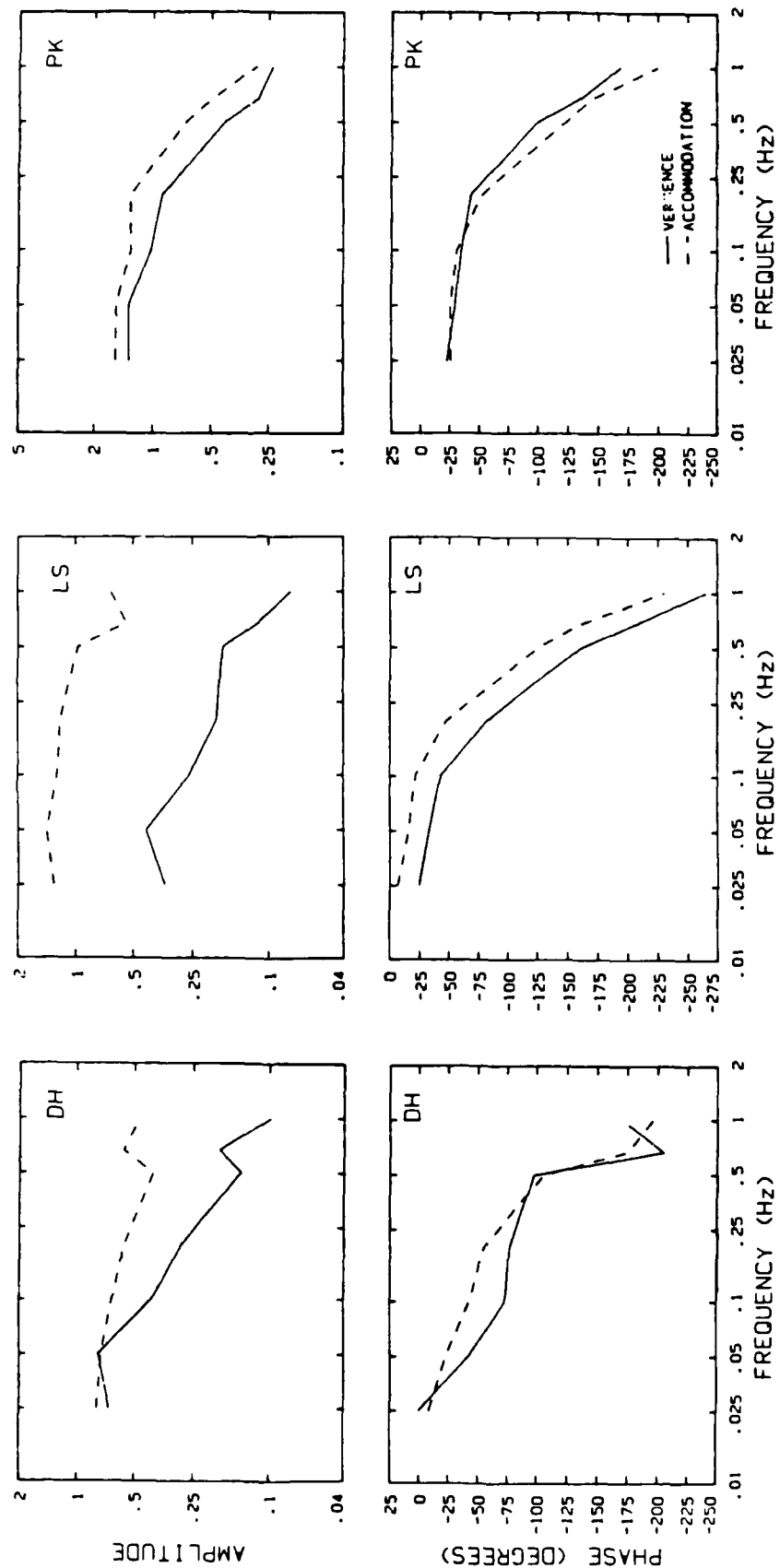
Fig. 10. Plots, for three subjects, of response amplitudes and phase of accommodation and vergence vs. frequency of stimulus. The stimulus is changing disparity of 0.8 meter angles (5 prism diopters). The amplitude of vergence is measured in meter angles and the amplitude of accommodation is measured in diopters. The phase of accommodation and vergence are plotted relative to the phase of the changing disparity stimulus.

DISPARITY AS STIMULUS
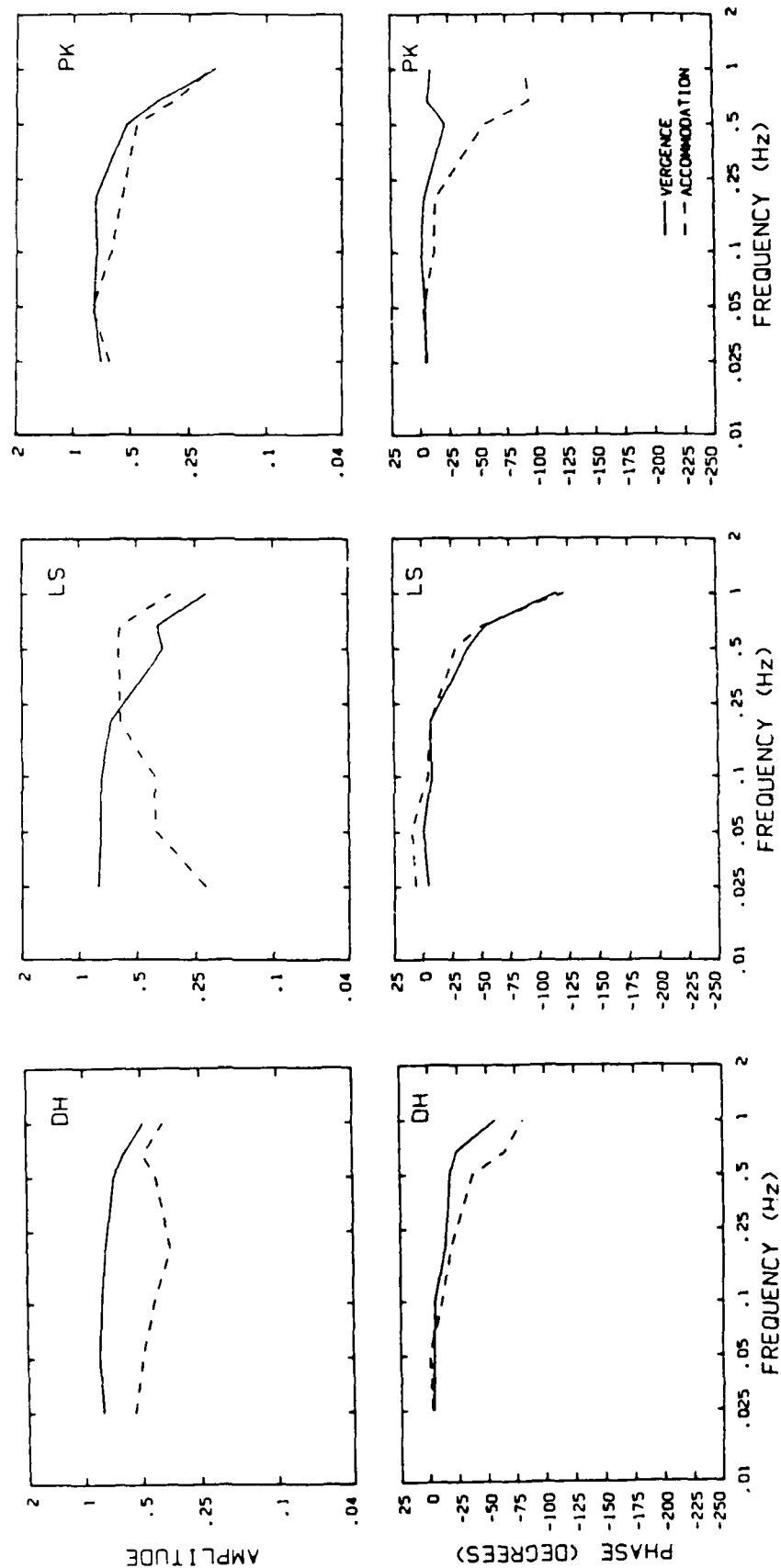
Fig. 11. Plots, for three subjects, of response amplitudes and phase of accommodation and vergence vs. frequency of stimulus. The stimulus is changing blur of 1.67 diopters combined with 4X size change. The amplitude of vergence is measured in meter angles and the amplitude of accommodation is measured in diopters. The phase of accommodation and vergence are plotted relative to the phase of the changing stimulus.

BLUR + SIZE AS STIMULUS
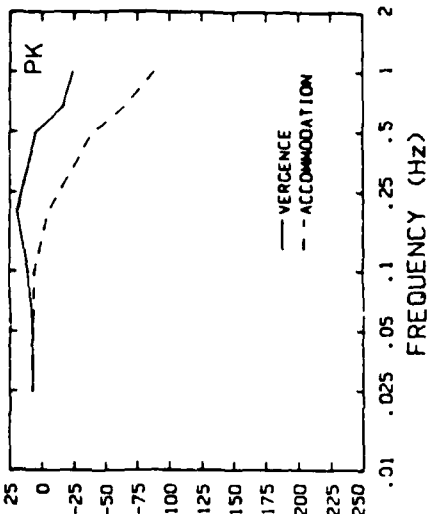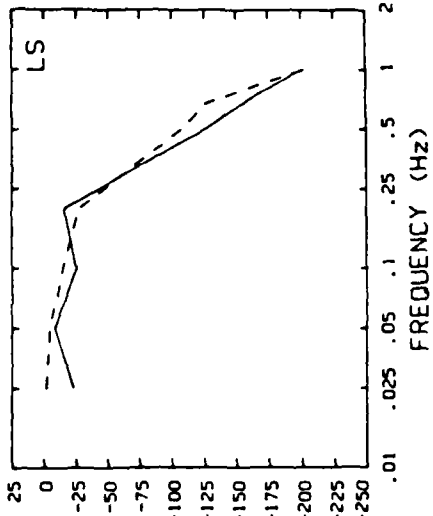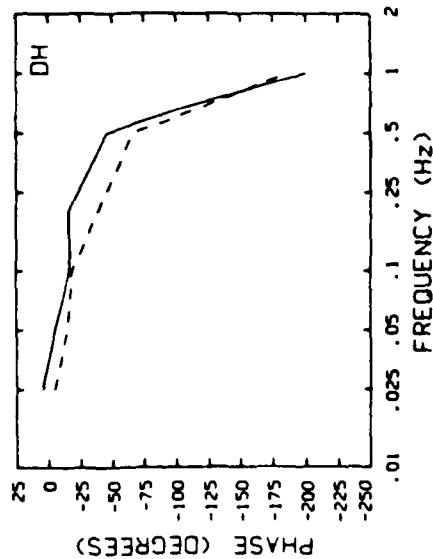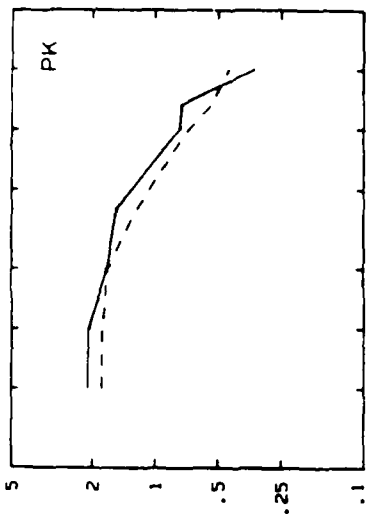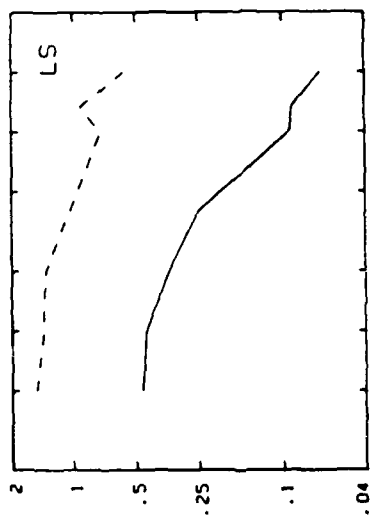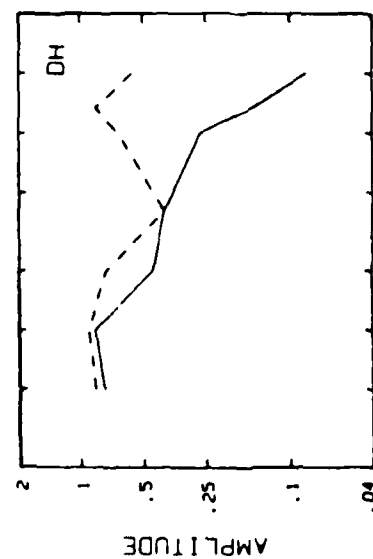
Fig. 12. Plots, for three subjects, of response amplitudes and phase of accommodation and vergence vs. frequency of stimulus. The stimulus is changing disparity of 5 prism diopters combined with a 4X size change. The amplitude of vergence is measured in meter angles and the amplitude of accommodation is measured in diopters. The phase of accommodation and vergence are plotted relative to the phase of the changing stimulus.

DISPARITY + SIZE AS STIMULUS

80
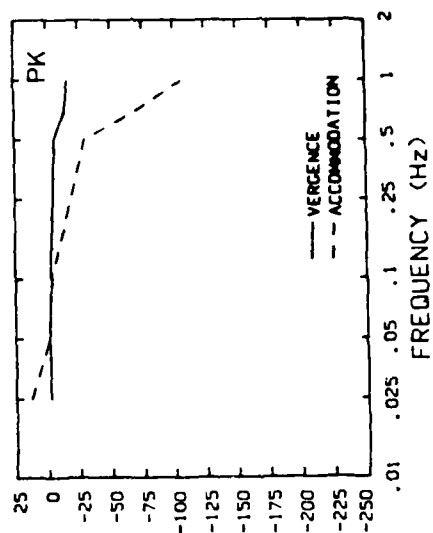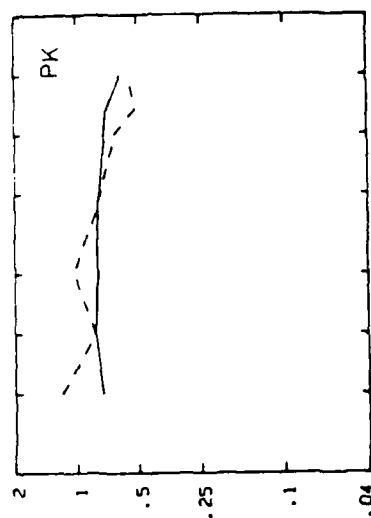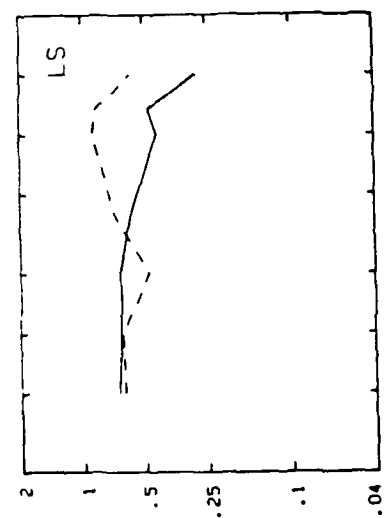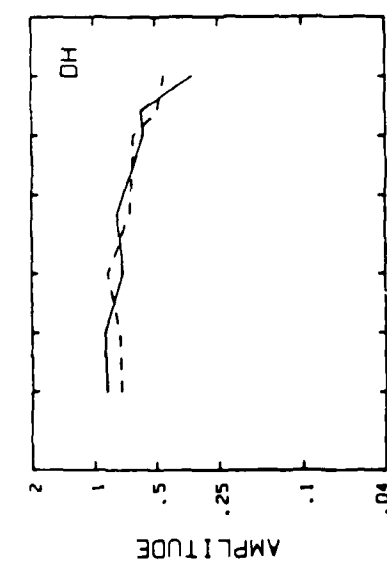
Fig. 13. Plot, for three subjects, of the response AC/A ratio to blur and to size vs. the frequency of the stimulus. The ratio is expressed in meter angles per diopter.
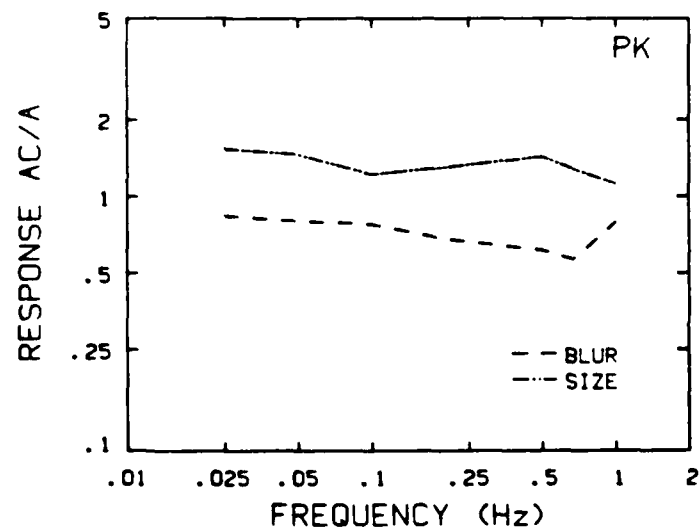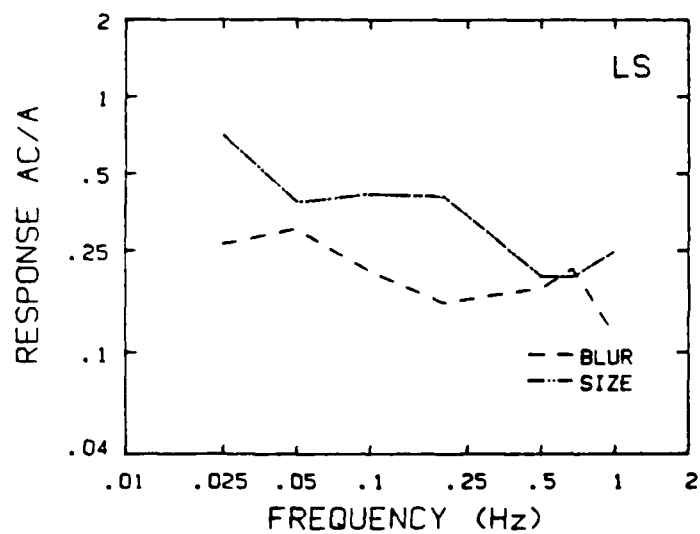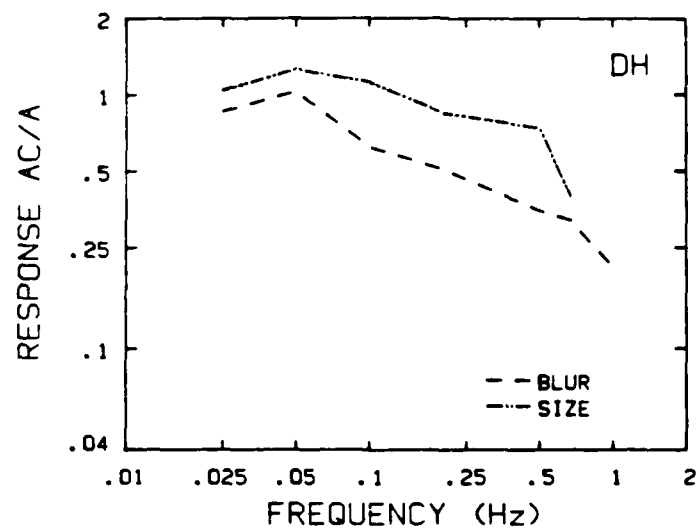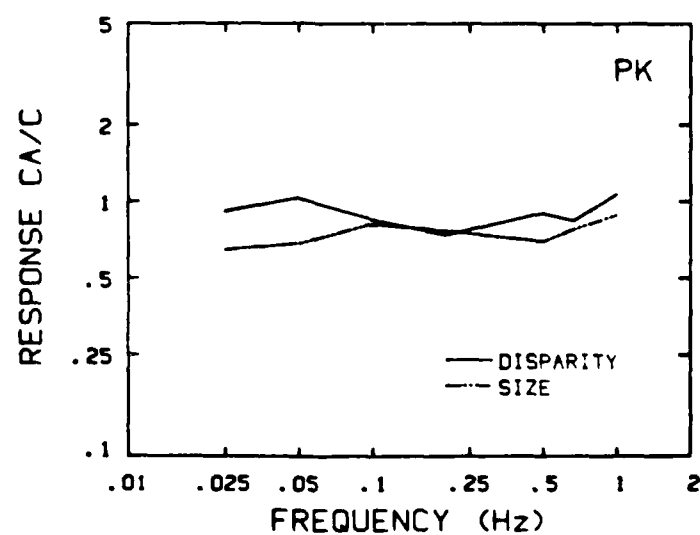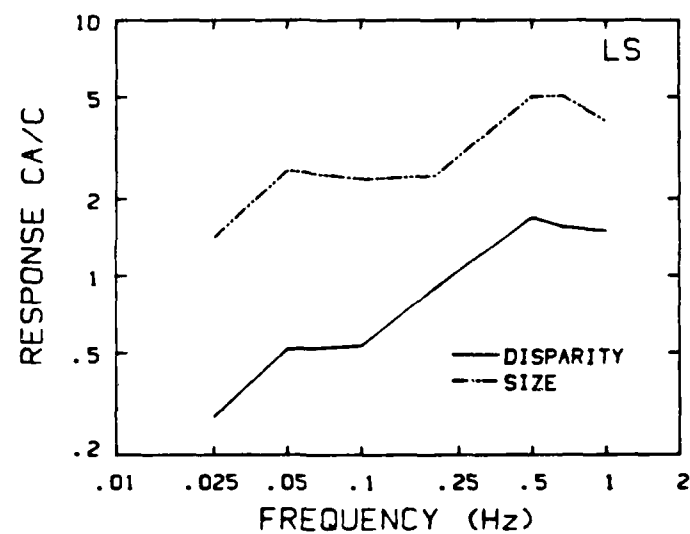
Fig. 14. Plot, for three subjects, of the response AC/A ratio to blur plus size and to blur alone vs. the frequency of the stimulus. The ratio is expressed in meter angles per diopter.
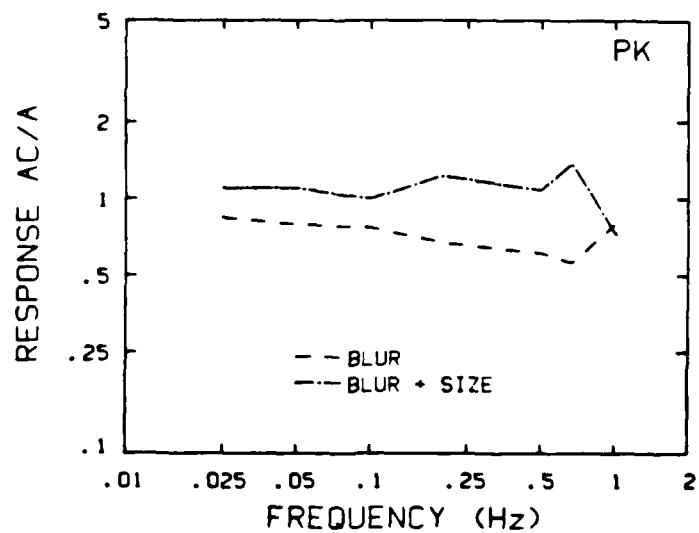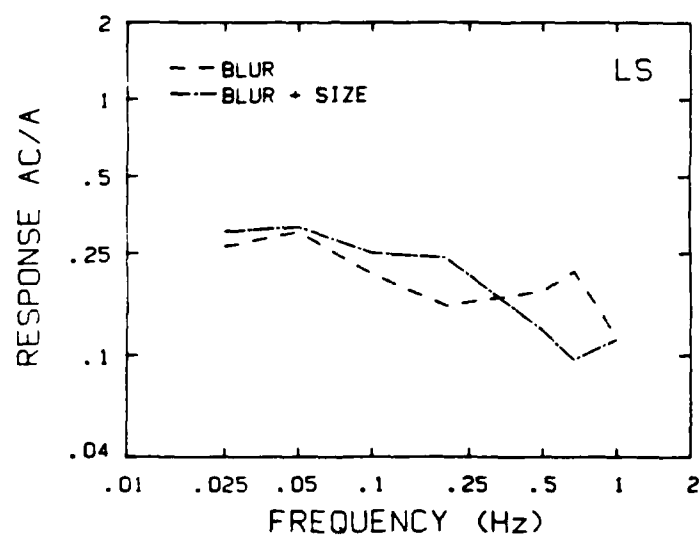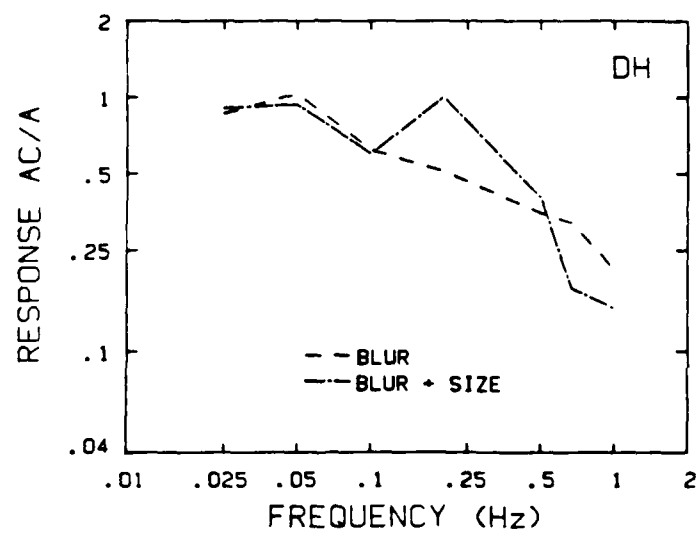
Fig. 15. Plot, for three subjects, of the response CA/C ratio to disparity and to size vs. the frequency of the stimulus. The ratio is expressed in diopters per meter angle.
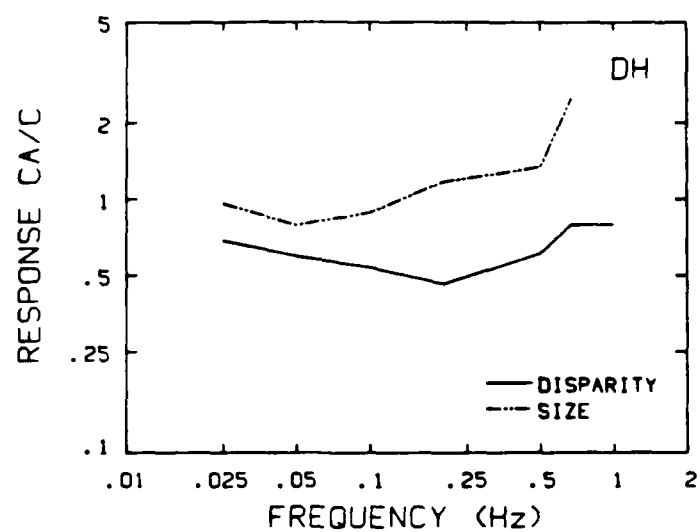
Fig. 16. Plot, for three subjects, of the response CA/C

ratio to disparity plus size and to disparity alone vs. the

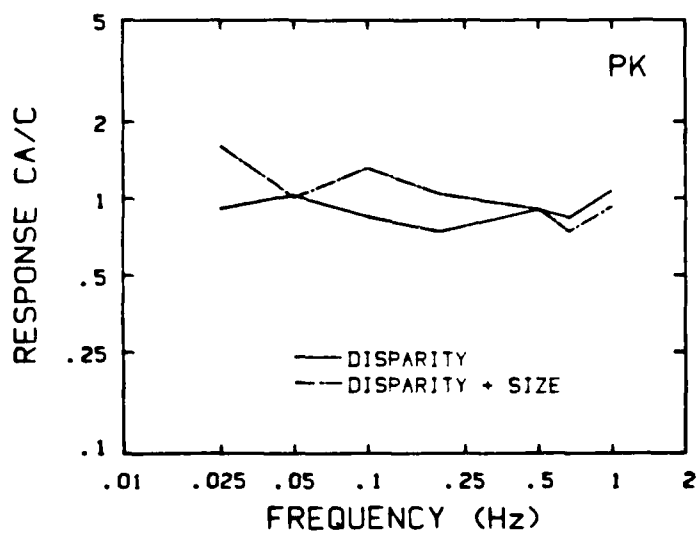frequency of the stimulus. The ratio is expressed in
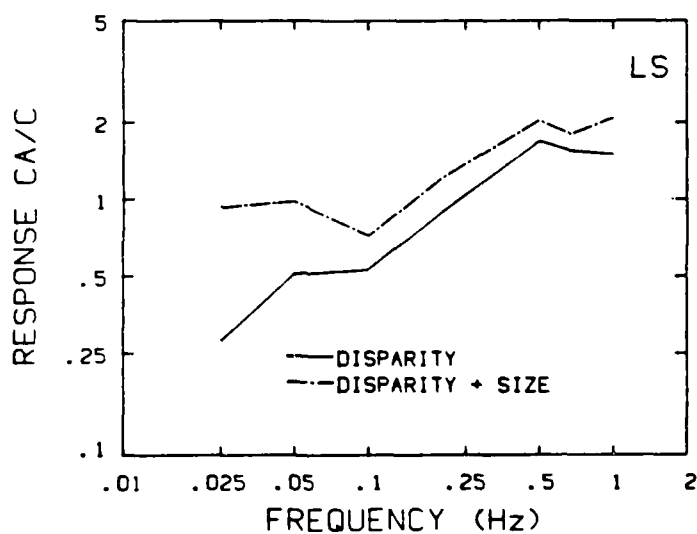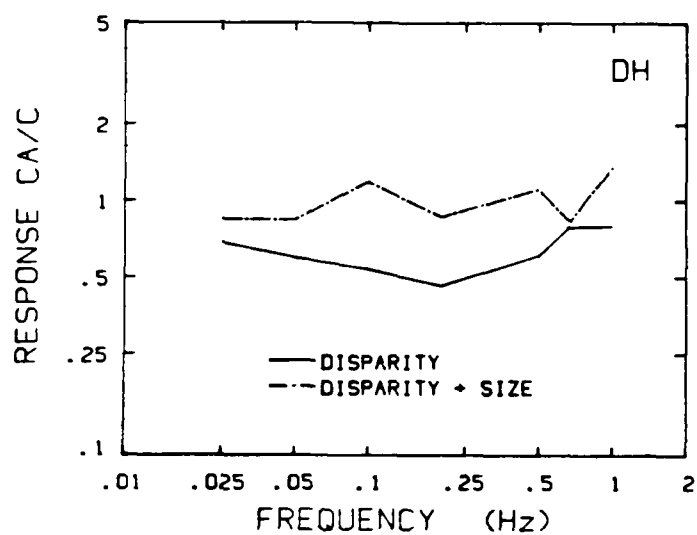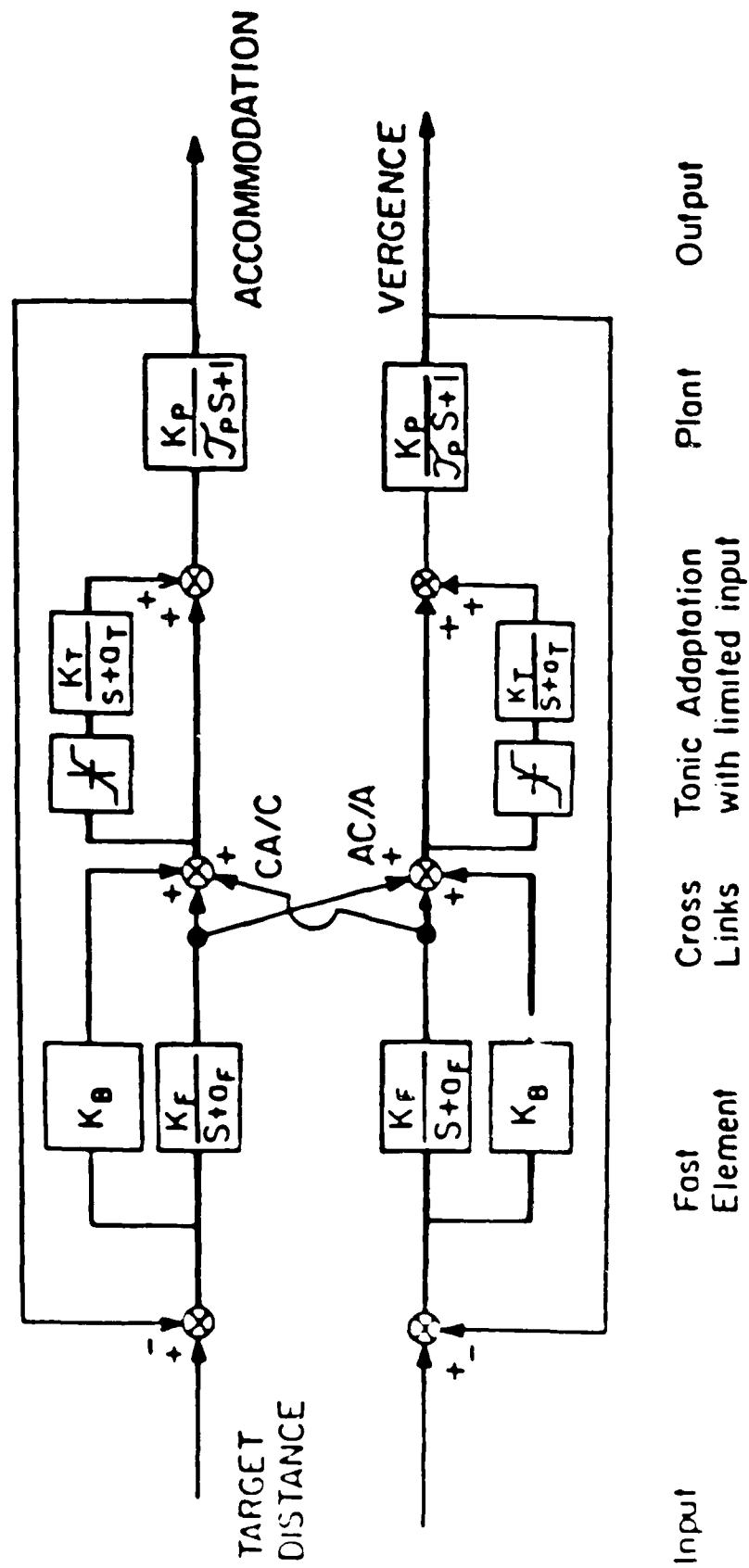
diopters per meter angle.

Fig. 17. Schor and Kotulak's (1986) system model of accommodation and vergence. The two motor systems are interconnected by separate AC/A and CA/C crosslinks. These crosslinks occur between the proposed phasic and tonic integrators of each system.
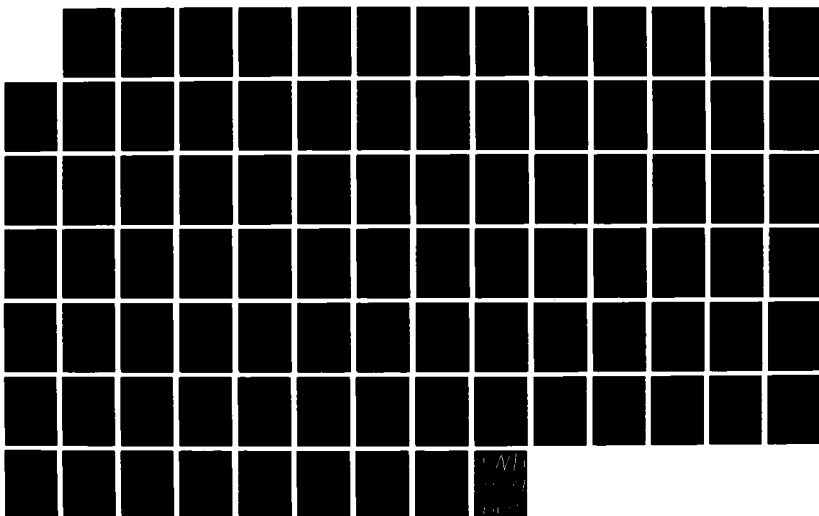
ACCOMMODATION

VERGENCE

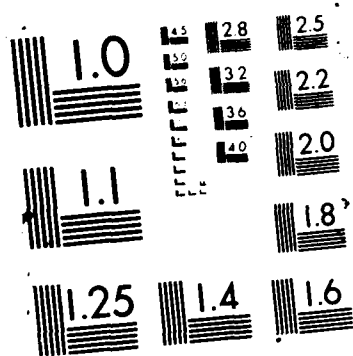| Input | Fast Element | Cross Links | Tonic Adaptation with limited input | Plant | Output |

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Chapter 3

Voluntary Effort as a Stimulus to Accommodation and Vergence

Most people can voluntarily cross their eyes and change
their accommodation, but it is not obvious whether they are
primarily accommodating, converging, or exercising both
voluntarily. A number of investigators have studied
voluntary accommodation. Marg (1951) studied seven
optometry students who professed to the ability to change
their accommodation voluntarily. While fixating a target
monocularly, with accommodation closed loop, most were able
to both positively and negatively accommodate from the
target. Westheimer (1957) had his subjects think of objects
near and far and noted accommodative changes of .5 diopters.
However, Campbell and Westheimer (1960) recorded voluntary
accommodative changes of over 3 diopters and found responses
of accommodation to blur combined with size change to be
like voluntary changes of accommodation. Others have
studied voluntary accommodation and training. Randle (1970)
trained subjects to change accommodation voluntarily and
Cornsweet and Crane (1972) also trained accommodation.
Malmstrom and Randle (1976) found naive subjects could
affect accommodation with visual imagery. Provine and Enoch
(1975) demonstrated trained subjects could use voluntary
accommodation to overcome the blur induced by a -9 diopter

contact lens. While these studies generally noticed that voluntary accommodation also elicited a vergence change, it was not determined whether accommodation was following vergence or vice versa.

Eskridge (1971) reported effects of voluntary effort upon accommodation and vergence. He found the "blur AC/A" ratio to be equivalent to changes in accommodation and vergence during voluntary vergence. Bobier (1964) measured the velocity of binocular vergence movements and reported that the velocity of convergence increased with practice and was faster than reflex vergence responses to disparity. From this, he concluded that the movements were voluntary. Accommodation associated with voluntary vergence was not measured in his experiments. Randle (1974) found that the velocity of accommodation increased with practice. These reports indicate a voluntary component in vergence and accommodation that has a higher velocity limit than reflex responses to disparity and blur respectively.

I examined both accommodation and vergence when voluntary changes were made to imagined changes in target distance and found that accommodation and vergence had a ratio similar to the blur driven AC/A ratio but not the disparity driven CA/C ratio. Accommodation appears to be driving the vergence response. Therefore, voluntary vergence seems to be roughly equivalent to accommodative vergence.

Methods:

Apparatus

The same instrumentation, the SRI dual-Purkinje-image eyetracker and dynamic optometer that was described in chapter 1, was again used in this experiment. The same strip chart was used to record responses and the same video display of a Maltese cross was used. Its size was approximately 46 mm at 67cm (4 degrees).

Recordings of the responses of accommodation and vergence were digitized at 50 Hz on line for one subject so that the maximum velocities of the accommodative response could be determined.

Experimental procedures

The subjects were dilated with 2.5% phenylephrine hydrochloride, a weak sympathomimetic at the start of the experimental sessions in order to prevent pupillary artifacts in the measurement of accommodation and vergence. Phenylephrine does not change the AC/A ratio (Sabin and Ogle 1958). A mouthbite and forehead rest were used to avoid artifacts from movement of the subject. In this experiment the Maltese cross always remained the same size (4 degrees) and the subject viewed the cross monocularly through a 0.5 mm pinhole pupil. Ripps et al. (1972) have shown that this size pupil effectively opens the accommodative loop. The room was darkened so that the white cross was the only

object visible to the subjects. The subject was told to
"think near or look near" or "think far or look far" in
order to elicit changes in accommodation and vergence. They
were to do this while always maintaining fixation on the
center of the Maltese cross. Initially, they were given
some feedback by the experimenter as to the direction and
magnitude of their motor responses to these voluntary
efforts. The experimenter watched the strip chart during
the responses and if accommodation and vergence increased on
command the subjects were given the verbal feedback to
continue their current response. If the response was so
large that that the recording was saturated, they were told
to reduce their response. The subjects would generally stop
increasing accommodation and convergence when told to do so.
For comparison to the blur driven AC/A ratio, a "voluntary
AC/A ratio" was computed by dividing the changes in vergence
by the changes in accommodation to voluntary efforts. Three
to 5 responses were averaged to determine the "voluntary
AC/A ratio" for each subject. For comparison to the
disparity driven CA/C ratio, a "voluntary CA/C ratio" was
computed by dividing the changes in accommodation by the
changes in vergence to voluntary efforts.

The blur driven AC/A ratio was determined from the
responses of accommodation and vergence to monocular step
changes in blur of 1 and 2 diopters. The blur stimulus was
approximately the magnitude of the voluntary changes in

accommodation that the subjects made. At least 3 responses were averaged in order to determine the AC/A ratio. The blur stimulus was generated with Badal type stimulus optometer so that target size and brightness did not change with the changes in blur. The subjects viewed the targets monocularly through a 4 mm artificial pupil.

The disparity driven CA/C ratio was determined from the responses of accommodation and vergence to an asymmetric step disparity stimulus of 5 or 10 prism diopters to the left eye. The disparity stimulus was asymmetric to avoid changes in position of the right eye that might influence the measurement of that eye's accommodation. At least three responses were averaged in order to determine each subject's CA/C ratio. The subjects viewed the center of the cross binocularly through .5 mm pinhole pupils for this determination of the CA/C ratio.

The measurements of AC/A and CA/C ratios were also made at the end of an experimental session in which the subjects were presented a number of sinusoidal stimuli of changing blur, disparity, and size. The order of the types of measurements was randomized.

Subjects

Eight subjects, ages 18 to 38, were used. Six of the subjects were also used in the experiment on changing size. All subjects had normal stereopsis and acuities that were

correctable to at least 20/20 in each eye. Their amplitudes of accommodation were normal for their ages. One of the subjects, PH, had a divergence excess of 15 prism diopters at distance that was well controlled. This subject had orthoptics in the past and had worked as an orthoptist.

Results:

Voluntary responses of accommodation and vergence compared to the "blur AC/A ratio"

Figure 1 plots the "blur AC/A ratio" against the "voluntary AC/A ratio." The units are meter angles per diopter for both of these response AC/A ratios. The dashed line is the 1:1 line and a good correlation is obvious (r=.9298). Only one point by inspection appears to be significantly off the 1:1 line. To check whether the "blur AC/A ratio" is significantly different from the "voluntary AC/A ratio" a paired T test was done and there was not a significant difference (t_7= -1.40, p=.20)

Voluntary responses of accommodation and vergence compared to the "disparity CA/C ratio"

Figure 2 plots the "disparity CA/C ratio" against the "voluntary CA/C ratio" and the points are well scattered (r=.4499). Voluntary effort causes accommodation and vergence to respond in amounts more characteristic of the AC/A ratio than the CA/C ratio. A paired T test between the "disparity CA/C ratio" and the "voluntary CA/C ratio" shows a significant difference (t_7=-2.55, p = .038). Only one point is obviously on the 1:1 line.

One way to look at the results from the raw recordings is to look at the amplitude of convergence in meter angles relative to the amplitude of accommodative response. A

typical example is shown for subject HB in figure 3. For
the "blur AC/A ratio" (figure 3. a.) the accommodative
response is larger than the vergence response, but for the
"disparity CA/C ratio" (figure 3. b.) the vergence response
is larger than the accommodative response. For the
voluntary change (figure 3. c.), the accommodation is also
larger than the vergence. This is the pattern for 7 of the
8 subjects for AC/A and 5 of the 8 subjects for CA/C.

Subject PK in figure 4 is atypical in that he has an
AC/A ratio that is much higher than the others. However this
subject is typical in that his voluntary effort causes
changes in accommodation and vergence that are more like his
AC/A ratio than his CA/C ratio. The one subject that is
off the line for "blur AC/A ratio" vs. "voluntary AC/A
ratio" is on the line for "disparity CA/C ratio" vs.
"voluntary CA/C ratio." This is subject PH who has a
divergence excess (exophoria higher at far than near).

Velocity of the accommodative response

In one subject, we measured the peak velocity of the
accommodative response to blur and the peak velocity of the
accommodative response to voluntary efforts. The third
curve from the top in figures 5 and 6 plots the
instantaneous velocity of accommodation obtained by
differentiation of the accommodative response curves. For a
1.5 diopter accommodative response, the maximum velocities

for increasing and decreasing accommodation were very
similar for blur driven and voluntary responses (2 to 3
diopters/second). The ratio of vergence to accommodation
for this subject was 1 meter angle per diopter for voluntary
changes or blur induced changes in accommodation and
vergence. The similarity of maximum velocities for
accommodation and the similarities of the ratios for both
stimulus conditions is more support for the hypothesis that
voluntary effort is driving accommodation directly.

General Observations

Generally, the subjects required very little
instruction in order to have them elicit voluntary changes
in vergence and accommodation. They would be able to make
responses and at the same time maintain fixation on the
center of the cross on their first attempt. However, one of
the subjects used in the experiment on the effect of
changing size was unable to make voluntary changes even
though he responded to changing size. Another subject,
required two sessions in order to "learn" to make voluntary
responses. While they could easily make these voluntary
changes, they were generally unable to verbalize what they
were doing.

There was variability between subjects in the magnitude
of the accommodative responses from .5 to over 4 diopters
and the vergence from 2 prism diopters to over 15 prism

diopters. One of the subjects would sometimes reduce accommodation when told to "think near" and increase accommodation when told to "think far." At other times she would respond in the appropriate directions. She was unable to verbalize just what the difference was in the two responses.

One subject, unexpectedly, was found to have two types of voluntary response. Usually, her voluntary efforts evoked accommodation and vergence equal to her "blur AC/A ratio" but she also demonstrated some voluntary responses which consisted of accommodation of up to 3 diopters and little or no vergence even though one eye was occluded. This was unlike her AC/A and CA/C ratios. Figure 7 shows these different responses. We subsequently tested this subject several times. At first we were unable to get her to repeat this response of accommodation without convergence. However, by trial and error we discovered that she would accommodate without converging when told to look through the center of the cross. This instruction would repeatedly elicit accommodation with little or no vergence and this was very different from her usual voluntary response. To rule out the possibility of vertical movements causing an artifact in the accommodative recording, vertical position was recorded. Vertical eye movements were not present when she voluntarily accommodated without converging. These unusual responses were not used in

comparing the voluntary responses to the AC/A and CA/C ratios.

After checking responses to "thinking near" and "thinking far" we had a few of the other subjects try to voluntarily cross their eyes without accommodating or accommodate without crossing their eyes. Except for RP they were unable to respond any differently with these instructions and still responded in a "blur AC/A ratio." In addition, responses without the cross as a target in the dark were also like the "blur AC/A ratio."

Discussion:

Voluntary accommodation and the AC/A ratio

The voluntary changes in accommodation and vergence of
our subjects had a ratio equal to the "blur AC/A ratio".
Eskridge (1971) in a study of voluntary vergence, found
accommodative vergence to be no different than voluntary
vergence. Unfortunately, accommodation was not open loop in
his experiment. Despite this, he concluded that "voluntary
vergence" appears to be produced voluntarily through the
stimulation of accommodative vergence. We measured
voluntary changes with both accommodation and vergence open
loop and came to the same conclusion as Eskridge. Voluntary
efforts of accommodation resulted in an accommodative
vergence response.

Accommodation without vergence

While attempting voluntary accommodation, with one eye
occluded, one subject was able to respond without any
accommodative vergence. This discovery of accommodation
that was not associated with vergence was surprising.
Though we were only able to elicit this response in one
subject, we speculate that it may be present in others. We
hypothesize that this voluntary accommodative response may
be present in some unusual accommodative vergence responses
that we have encountered. In these responses, the
accommodative vergence velocity appears to be unusually slow

after a blur stimulus is presented. See figure 8 for an example of this. Possibly voluntary accommodation that bypasses the AC/A crosslink could be causing a quick response of accommodation and as the normal phasic accommodative controller takes over, vergence slowly increases.

We did not find any cases of voluntary effort resulting in vergence without a change in accommodation. Hofstetter (1942), Morgan (1944), Ogle and Martens (1957), Alpern (1958) and others have all found evidence for proximal vergence that is generally assumed to be independent of accommodation. If vergence were being produced without accommodation, then in Schor's model (figure 9), voluntary vergence would enter the vergence loop after the CA/C crosslink.

Proximal Accommodation

Proximal accommodation is one possible explanation for the voluntary responses that were elicited. A "voluntary" perceived distance may be driving accommodation and accommodative vergence may be responding through the AC/A crosslink. Ittleson and Ames (1950) have reported proximal accommodation. The responses, reported in chapter 2, to changing size might be due to proximal accommodation. Perhaps visual imagery was used to produce the proximal accommodation. Malmstrom and Randle (1976) and Westheimer

(1957) both found that visual imagery could be used to produce changes in accommodation. Indeed, some of the subjects reported that they used visual imagery when making voluntary changes in accommodation and vergence.

Proximal vergence, on the other hand, is not consistent with our results. If proximal vergence were the driving force for our voluntary responses, then a CA/C ratio response or a vergence response independent of accommodation would have been found rather than an AC/A ratio response.

Interactions in blur driven and voluntary accommodation

The easy elicitation, without time consuming training, of voluntary changes in vergence and accommodation suggests that voluntary effort may be an important component of accommodation in everyday situations. Cornsweet and Crane (1973) have pointed out that any cue might train the accommodative reflex. They add that a natural cue, such as changes in retinal image size that accompany the feedback of blur of the retinal image, might easily train the accommodative system. The fact that we found an AC/A response to changing size in chapter 1 suggests that changing size may be eliciting a type of voluntary response.

Campbell and Westheimer (1960) reported that the accommodative recordings were similar and occurred in single sweeps when voluntarily accommodating or responding to a blur stimulus combined with size cues. Responses to blur

alone were more likely to be variable in form and consist of more than one sweep. This implies that voluntary effort is significantly influencing the response.

Variations in the accommodative response characteristics to sinusoidal gratings have been partially attributed to the varying instructions given to the subjects (Owens 1980, Ciuffreda and Hokoda 1983, Tucker et al. 1986). Different subjects, as pointed out by Tucker et al. (1986) may use different accommodative strategies, and accommodation is not a simple reflex mechanism. In considering whether blur or the disparity stimulus is the primary stimulus to accommodation in natural environments, voluntary effects should also be considered. A "voluntary" accommodation may be an important component of accommodative vergence.

Response velocity of voluntary and blur driven accommodation

Our results for one subject indicate that the maximum velocity of the accommodative response with blur as a stimulus is similar to the maximum velocity of the accommodative response to voluntary effort. Tucker and Charman (1979) studied the dynamics of the accommodative response in two subjects and found substantial differences between these two subjects. They attributed these differences to differences in their capacity for voluntary control of accommodation. More work needs to be done on the

dynamics and velocity of the accommodative response and the effect of voluntary effort on these dynamics.

Effect of training on accommodation

Randle and Murphy (1974) studied the dynamic response of accommodation over a seven day period and found the velocity of accommodation to increase. Similarly, Liu et al. (1979) showed that in subjects with dynamic insufficiencies of accommodation, orthoptics treatment was associated with significant increases in the velocity of the accommodative response. These increases in the response of accommodation with repetition and training may be explained by a voluntary accommodation contributing to the response. In these cases, this voluntary accommodation can not be attributed to convergence accommodation.

The exceptional case of PH, in which voluntary efforts produced a ratio of accommodation and vergence equal to the CA/C ratio rather than AC/A ratio suggests that perhaps in some cases voluntary effort is directly driving vergence rather than accommodation. With PH's extensive background in orthoptics, perhaps she has somehow trained a different voluntary response for the vergence system that is analogous to voluntary responses of the accommodative system seen in other naive subjects..

Training or orthoptics might be expected to enhance a subject's awareness of the direction of voluntary

accommodation. While these accommodative responses were easily elicited, some subjects did not have a precise sense of where in space they were focusing or converging. In particular, subject LS would sometimes decrease her accommodation and vergence when told to focus at near. Marg (1951), similarly had 2 of 7 subjects negatively accommodate when attempting positive voluntary accommodation. The ability to sense direction of responses could be developed in a natural environment where there is feedback from blur.

A model of voluntary accommodation and vergence

In a dual component or interactive model of accommodation and vergence such as proposed by Semmlow and Hung (1980) or Schor and Kotulak (1986), our results suggest that voluntary effort is directly driving accommodation and that vergence is responding secondarily through the AC/A crosslink. Schor's model is shown in figure 9. It is possible to model voluntary effort with direct inputs on both the accommodation and vergence sides. However, direct stimulation of the accommodative loop by volition before the AC/A crosslink is the most parsimonious explanation. In cases of voluntary accommodation unaccompanied by convergence, the proportional gain element (K_B) which bypasses the crosslink (AC/A) would produce the results reported here. Hence we propose that only the fast neural integrator stimulates accommodative convergence and that a

nonintegrated component which enhances this frequency response of accommodation bypasses accommodative convergence. This model would predict that the velocity of accommodation could in some cases be much higher than the velocity of accommodative vergence. Indeed, this was demonstrated by the voluntary accommodative responses of RP (figure 7. d.). A related effect is the reduction of vergence accommodation produced by fatigue of accommodation by repeated measures of AC/A ratios shown in figure 10. Initially accommodative convergence follows accommodation but with fatigue, accommodative convergence is reduced. Possibly K_B is more active and K_F is less active with fatigue.

Summary:

With only minimal instruction and some verbal feedback of their responses, subjects could voluntarily elicit changes in accommodation and vergence. The accommodation and vergence responded in amounts typical of an AC/A ratio rather than a CA/C ratio. This implies that voluntary effort is driving accommodation primarily and that vergence is a secondary response through an AC/A crosslink. There may be other possible voluntary responses and one subject demonstrated voluntary accommodation without converging.

Voluntary accommodation should be considered as common and should be considered as a possible component in studies of reflex accommodation.

Fig. 1. Plot of blur AC/A ratio vs. voluntary AC/A ratio
for 8 subjects. The dashed line is the 1:1 line. The
correlation is strong (r = .9298). A paired T test between
the blur AC/A ratio and voluntary AC/A ratio does not show a
significant difference (p = .20). Units are meter
angles/diopter.
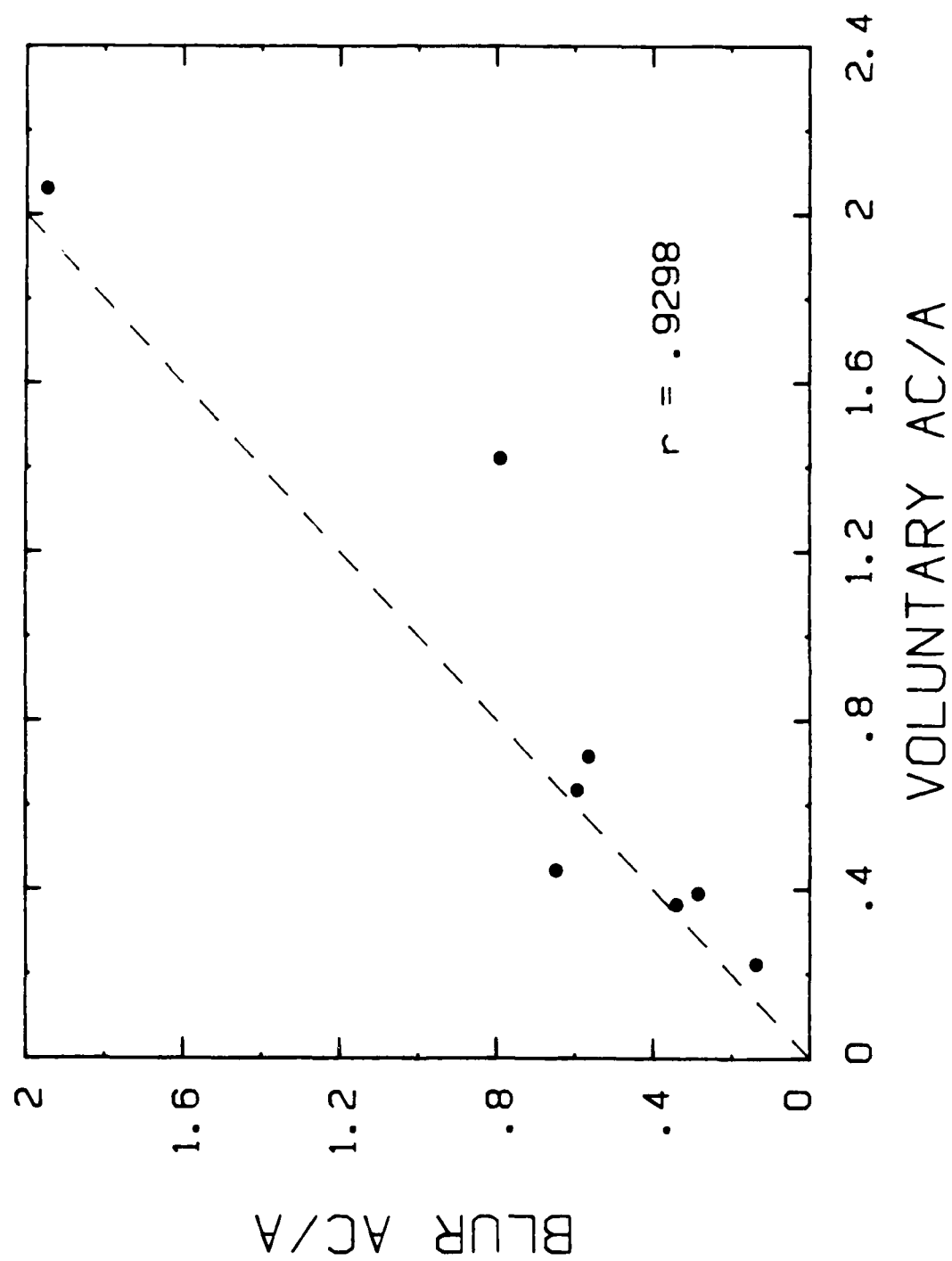
Fig. 2. Plot of disparity CA/C ratio vs. voluntary CA/C
ratio for 8 subjects. The correlation is weak (r = .4499).
The dashed line is the 1:1 line. A paired T test between the
disparity CA/C ratio and voluntary CA/C ratio
shows a significant difference (p = .038). Units are
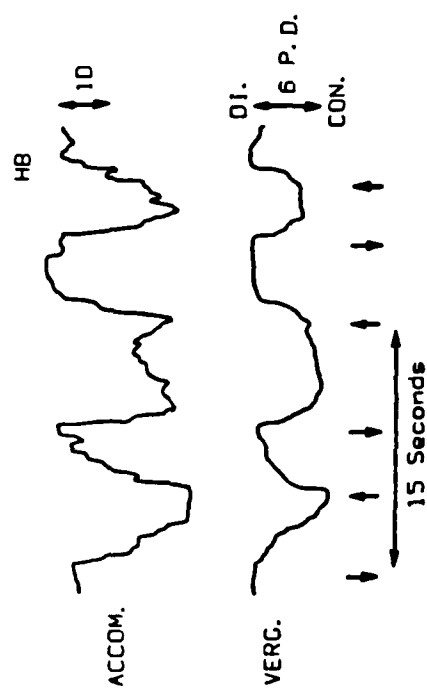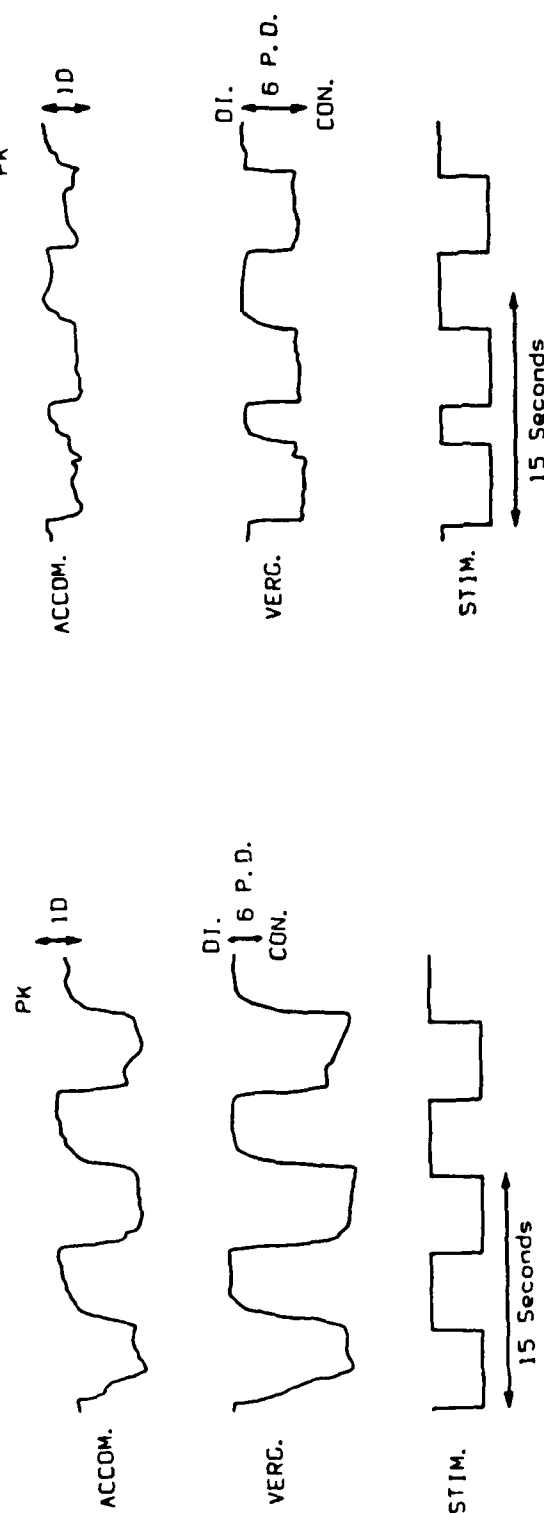diopters/meter angle.
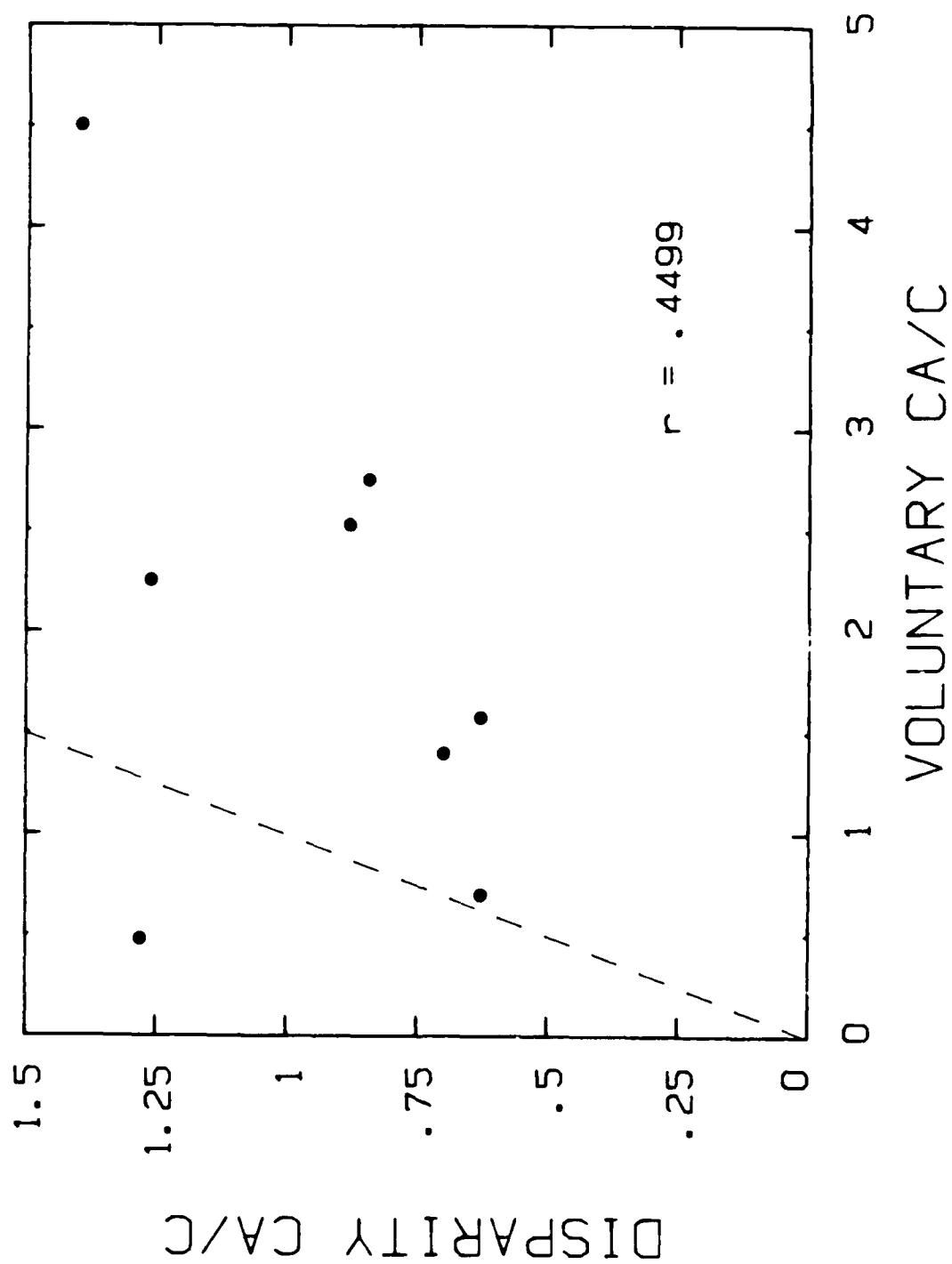
Fig. 3. Subject H.B.: a. Accommodative and vergence responses to step increases and decreases in blur of 1.75 diopters. Convergence and accommodation increased with downward movement of the lines. The subject viewed the Maltese cross monocularly through a normal sized pupil. The AC/A ratio is determined by dividing the change in vergence by the change in accommodation.

b. Accommodative and vergence responses to step increases and decreases in disparity of 5 prism diopters. Convergence and accommodation increased with downward movement of the lines. The subject viewed the Maltese cross binocularly through pinhole pupils. The CA/C ratio is determined by dividing the change in accommodation by the change in vergence.
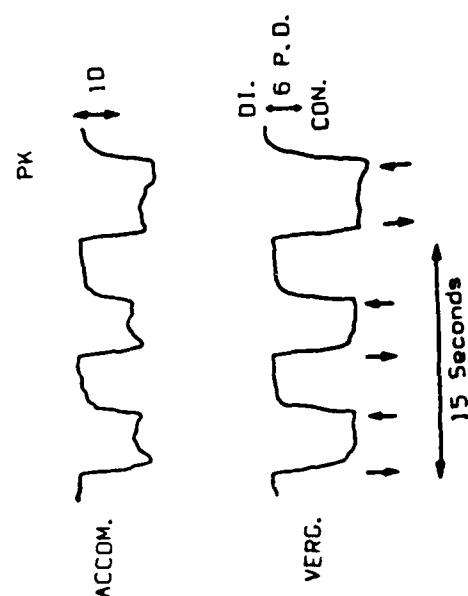
c. Accommodative and vergence responses to voluntary effort. Convergence and accommodation increased with downward movement of the lines. The subject fixated the center of the Maltese cross monocularly through a pinhole pupil. Down arrows indicate instructions to the subject to "think near" and up arrows to "think far." For comparison to the blur driven AC/A ratio, a "voluntary AC/A ratio" is determined by dividing the change in vergence by the change in accommodation. For comparison to the disparity driven CA/C ratio, a "voluntary CA/C ratio" is determined by

dividing the change in accommodation by the change in vergence.

a. BLUR AS STIMULUS

b. DISPARITY AS STIMULUS

c. VOLUNTARY CHANGE

Fig. 4. Subject P.K.: a. Accommodative and vergence responses to step increases and decreases in blur of 1.75 diopters. Convergence and accommodation increased with downward movement of the lines. The subject viewed the Maltese cross monocularly through a normal sized pupil. The AC/A ratio is determined by dividing the change in vergence by the change in accommodation.

b. Accommodative and vergence responses to step increases and decreases in disparity of 5 prism diopters. Convergence and accommodation increased with downward movement of the lines. The subject viewed the Maltese cross binocularly through pinhole pupils. The CA/C ratio is determined by dividing the change in accommodation by the change in vergence.

c. Accommodative and vergence responses to voluntary effort. Convergence and accommodation increased with downward movement of the lines. The subject fixated the center of the Maltese cross monocularly through a pinhole pupil. Down arrows indicate instructions to the subject to "think near" and up arrows to "think far." For comparison to the blur driven AC/A ratio, a "voluntary AC/A ratio" is determined by dividing the change in vergence by the change in accommodation. For comparison to the disparity driven CA/C ratio, a "voluntary CA/C ratio" is determined by

dividing the change in accommodation by the change in vergence.

a. BLUR AS STIMULUS
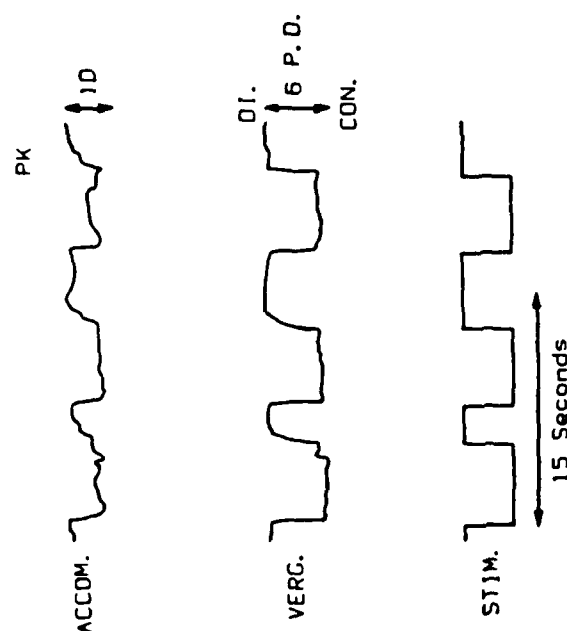
b. DISPARITY AS STIMULUS

c. VOLUNTARY CHANGE

Fig. 5. Response of vergence and accommodation to a 1.5 diopter blur stimulus with the left eye occluded. The third curve from the top is the velocity of accommodation and this is obtained by differentiation of the response of accommodation.
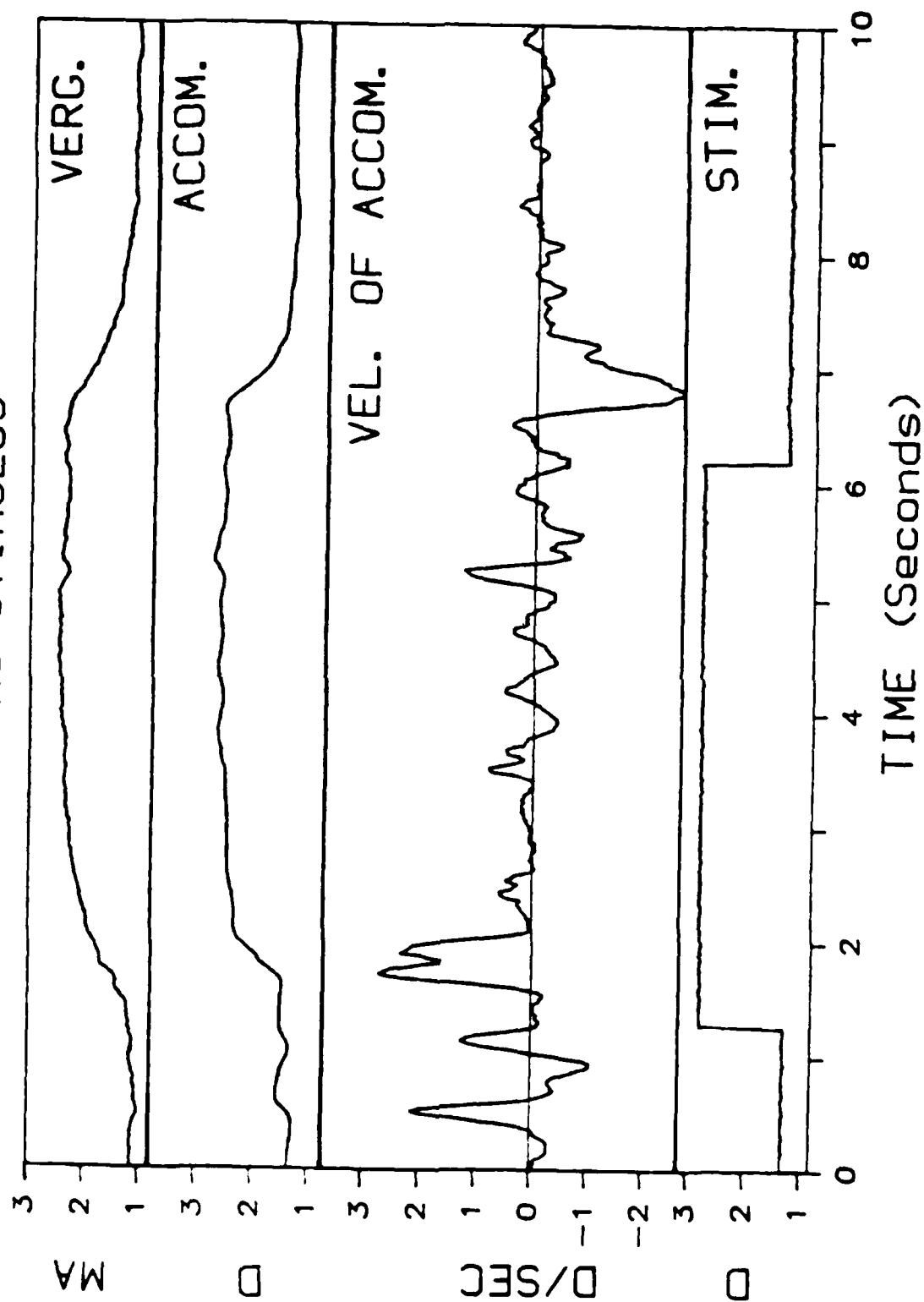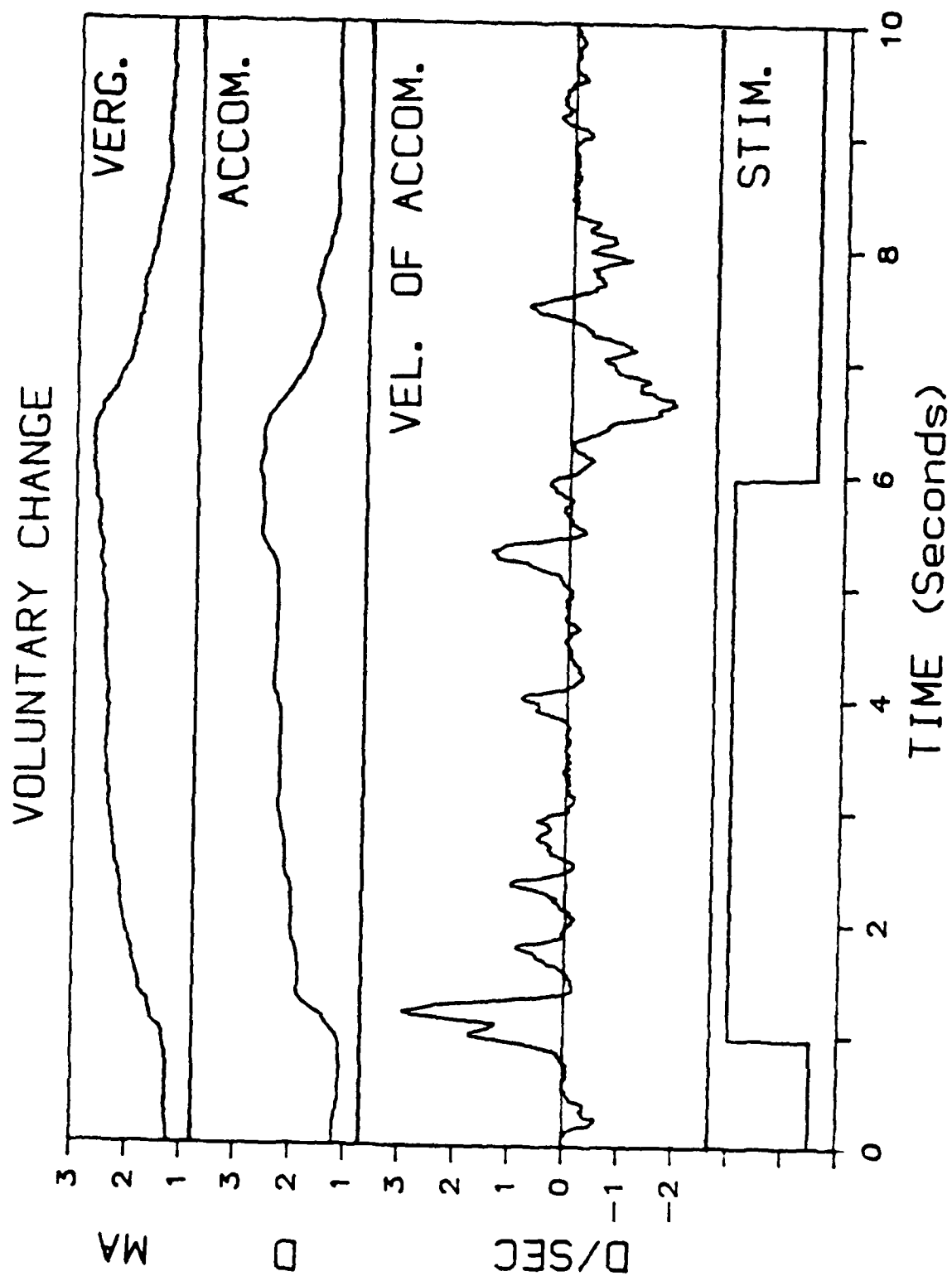
BLUR AS STIMULUS

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Fig. 6. Vergence and accommodation changes in response to
voluntary effort. The third curve from the top is the
velocity of accommodation and this is obtained by
differentiation of the response of accommodation.

Fig. 7. Subject RP: a. Accommodative and vergence responses to step increases and decreases in blur of 1.75 diopters. Convergence and accommodation increased with downward movement of the lines. The subject viewed the Maltese cross monocularly through a normal sized pupil. The AC/A ratio is determined by dividing the change in vergence by the change in accommodation.

b. Accommodative and vergence responses to step increases and decreases in disparity of 5 prism diopters. Convergence and accommodation increased with downward movement of the lines. The subject viewed the Maltese cross binocularly through pinhole pupils. The CA/C ratio is determined by dividing the change in accommodation by the change in vergence.

c. Accommodative and vergence responses to voluntary effort. Convergence and accommodation increased with downward movement of the lines. The subject fixated the center of the Maltese cross monocularly through a pinhole pupil. Down arrows indicate instructions to the subject to "think near" and up arrows to "think far." For comparison to the blur driven AC/A ratio, a "voluntary AC/A ratio" is determined by dividing the change in vergence by the change in accommodation. For comparison to the disparity driven CA/C ratio, a "voluntary CA/C ratio" is determined by
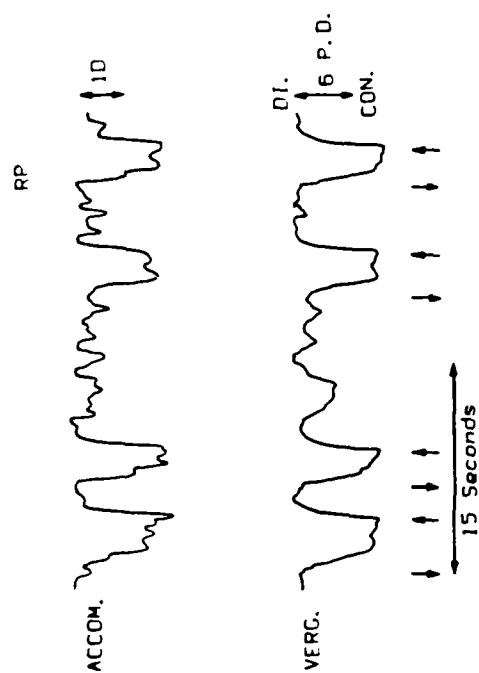
dividing the change in accommodation by the change in vergence.

d. These are the the same conditions as in 6.c. with the same subject RP. The responses, however are markedly different. Accommodation is responding without an associated vergence response.
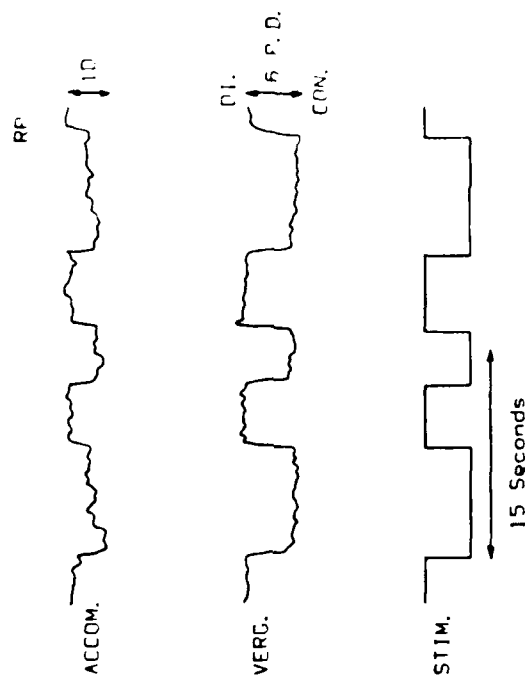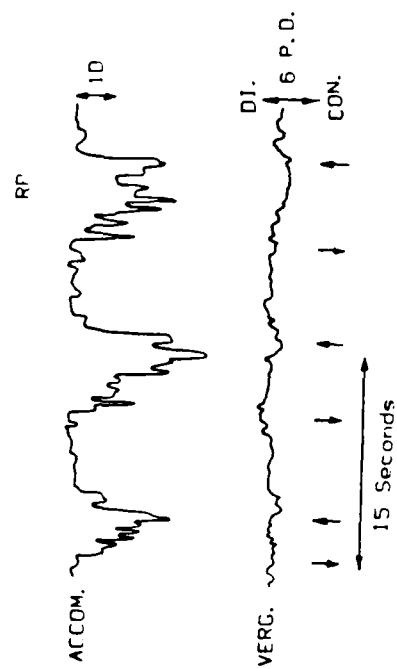
a. BLUR AS STIMULUS
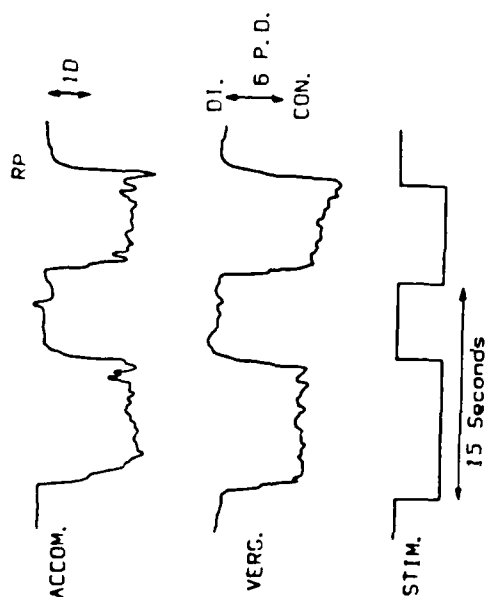
b. DISPARITY AS STIMULUS

c. VOLUNTARY CHANGE

d. VOLUNTARY CHANGE

Fig. 8. Response of accommodation and vergence to 1 and 2 diopter blur stimulus for subject TY. The accommodative vergence response is unusual in that it increases much more gradually than accommodation. This might be explained by voluntary effort causing the initial steep response of accommodation. Increased accommodation is in a downward direction in the top curve.
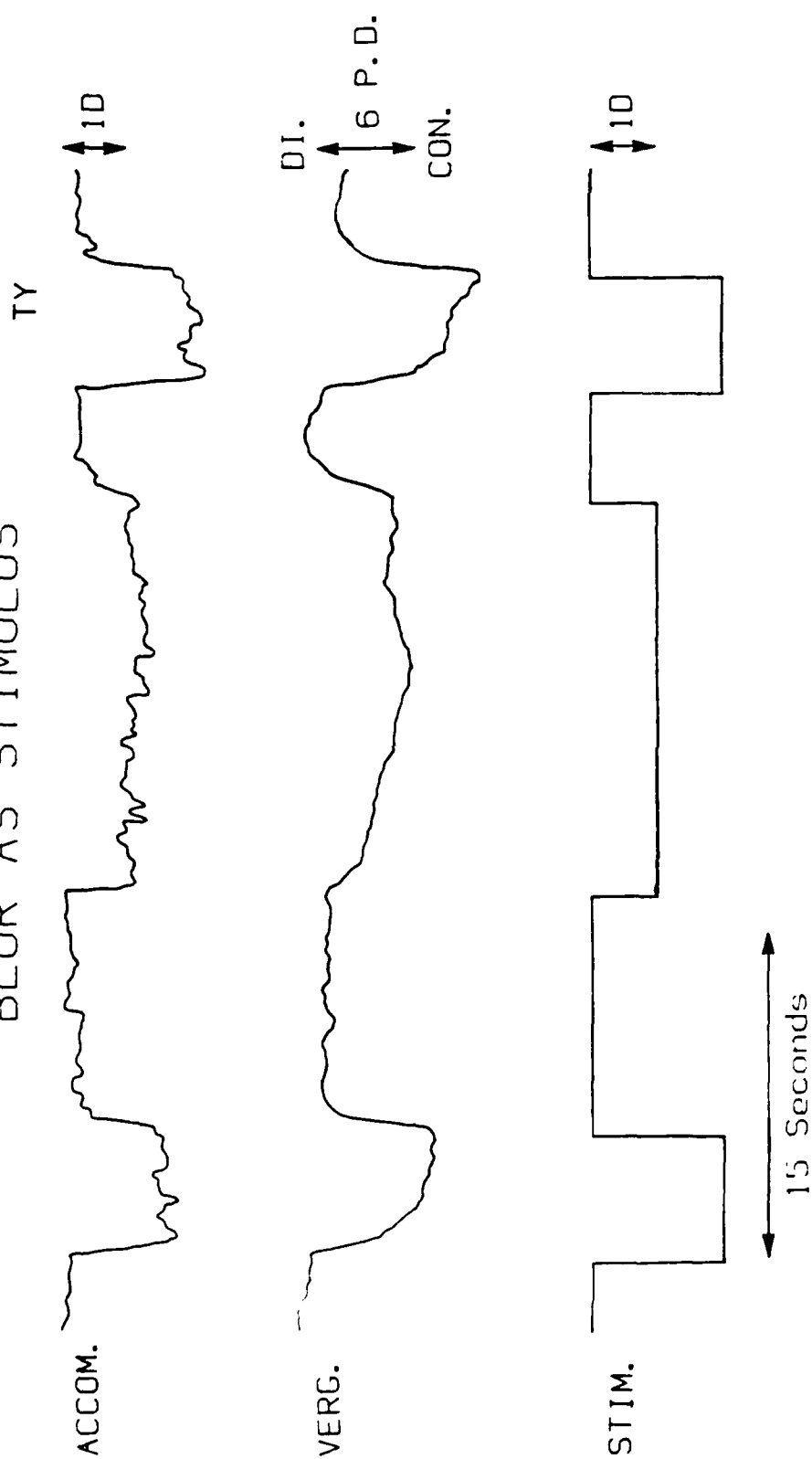
BLUR AS STIMULUS

Fig. 9. Schor's model (Schor and Kotulak 1986) of accommodation and vergence. The responses of accommodation and vergence to voluntary efforts suggest that voluntary effort causes an input to accommodation before the accommodative crosslink.
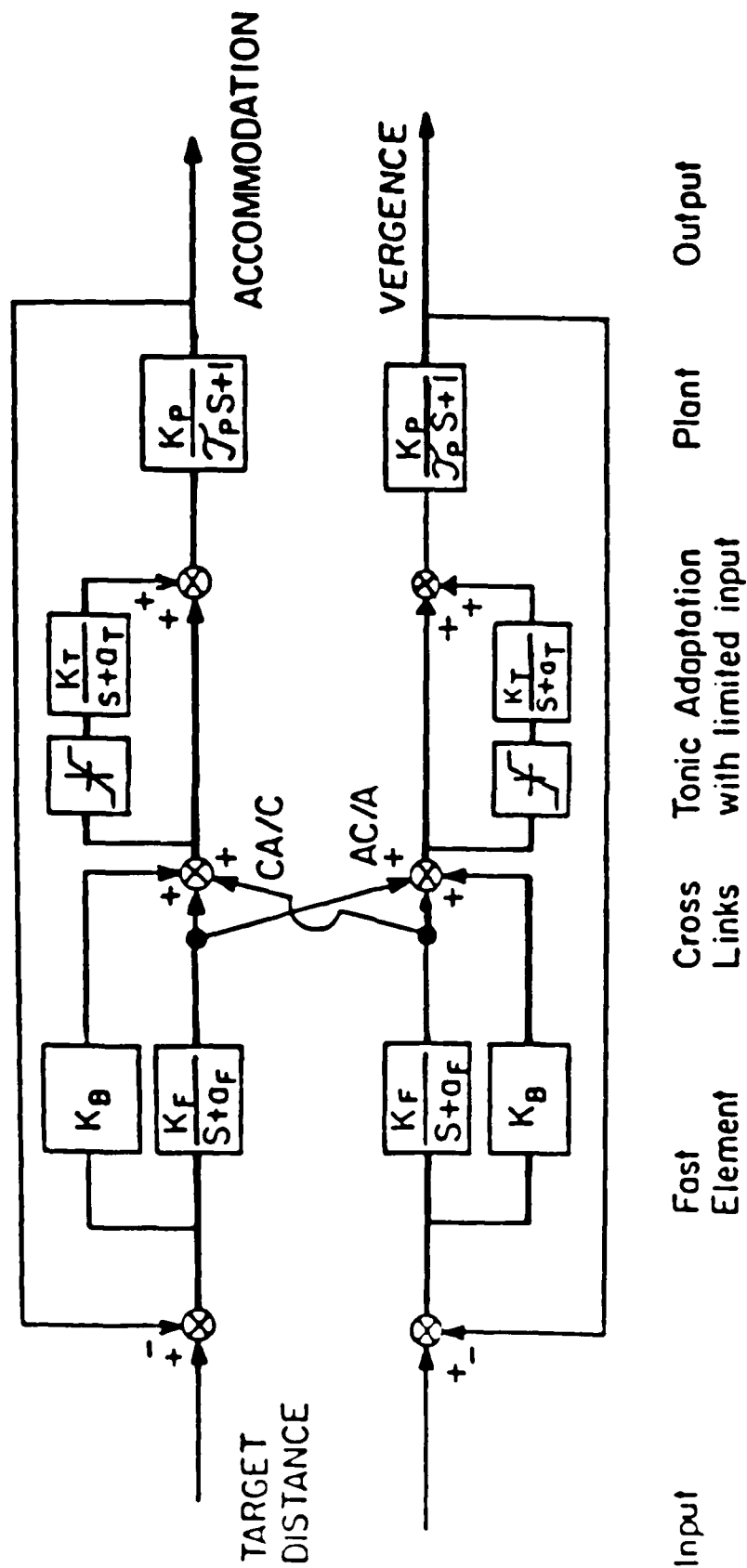
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Fig. 10. Step response of accommodative vergence for
subject JK. The accommodative vergence response is
decreased due to fatigue.

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Chapter 4

The Effect of Luminance on Accommodative Aftereffects

The tonic dark focus is measured in the dark so that there is no visual input stimulus to accommodation. A number of researchers (Wolf et al. 1987, Ebenholtz 1983, 1985) have shown that the dark focus can be altered by a sustained accommodative stimulus. Generally though, these adaptation effects are small, a half diopter or so and short lived (Schor et al. 1984, Wolf et al. 1987). The tonic dark focus is equal to the resting focus measured when the accommodative loop is opened with a pinhole (Phillips 1974). Recently, however, Schor et al. (1986) have demonstrated that much larger adaptation effects can be measured after short stimulus periods if the accommodative loop is opened with a pinhole rather than darkness. In fact, with the stimulus durations that Schor et al. used, the dark focus was basically unchanged while there were sustained tonic adaptation effects of accommodation that were measurable if the accommodative loop was opened with a pinhole or a bright empty field. Similarly, Wolfe and O'Connell (1987) found subset of subjects with much larger aftereffects in a bright empty field than in the dark.

Campbell (1954), Finchan (1951), Crane (1966), and Johnson (1976) have concluded that the accommodation

stimulus is mediated by the cones with little participation on the part of the rods because the range of accommodation is reduced to a fixed focus position as luminance is reduced to mesopic levels. This fixed focus position is generally taken to be equal to the dark focus. In this study, we examined the effect of different luminance levels on accommodative aftereffects that were present when the accommodative loop was opened with a pinhole. It was determined that lowering luminance to mesopic levels (0.001 - 10 cd./m^2) would mask the accommodative aftereffects that were measured by opening the accommodative loop with a pinhole. The amount of masking depended on the mesopic level of luminance. Over a mesopic range of luminances, as luminance was lowered the accommodative aftereffect decreased toward the dark focus. A cone response is therefore suggested as an integral component in tonic adaptation of accommodation.

Methods:

Visual Stimulus

The target was a difference of Gaussian (DOG), which resembled a bright blurred vertical bar with dark blurred vertical bars on each side. The DOG had a center spatial frequency of 2.2 cycles per degree. This center frequency was chosen because Kotulak and Schor (1987) showed a drop off of accommodation for DOG targets at higher spatial frequencies as luminance decreased and reduced the DOG's visibility. The DOG's contrast was 100%. Fourier transforms of the luminance profiles revealed a bandwidth of .. octaves with a peak spatial frequency of 2.2 cycles per degree, which were the same as the mathematically predicted bandwidth and peak spatial frequency (Schor et al. 1984). The DOG was originally produced on a Tekronix Model 608 oscilloscope screen. The screen was photographed to produce a 35 mm color slide and the slide was projected to produce the target. The slide was projected to an effective distance of 200 cm from the entrance pupil of the eye. The vertical height of the lighted field subtended 10.9 degrees and its width subtended 15.6 degrees. Its average luminance was 15 cd/m^2 as measured with a "Litemate" photometer. The projector was surrounded with black felt so that there was extraneous light from the projector. Other lights in the

room were covered so that the target was the only source of light in the room.

Apparatus

The SRI dual Purkinje-image-eyetracker and dynamic optometer that was described in Chapter 1 was again used in this experiment. The lenses of the visual stabilizers in this instrument reduced the luminance by .3 log units. A 4 mm pupil was imaged in the subject's natural entrance pupil which was dilated to 6 mm with 2.5% phenylephrine. The use of a much stronger dosage of phenylephrine (10%) has been shown to have no effect on the resting focus of accommodation (Garner et al. 1983). A neutral density filter and a .5 mm pupil could be pivoted into the 4 mm aperture. Thus, the filter and large pupil could be replaced with the pinhole pupil without affecting the brightness of the target. The filter reduced the luminance 1.2 log units. This 1.2 log unit reduction , plus the .3 log unit reduction from the lenses produced an effective target luminance to the subject of .5 cd/m^2. With the pinhole in place the subjects' depth of focus was increased to at least ±3 diopters. The responses of vergence, left and right eye position and accommodation were recorded on a 4 channel strip chart and on magnetic tape.

Subjects

Three paid subjects were used. All three had persistent aftereffects of accommodation after stimulation with blur. When their accommodative loops were opened with a pinhole pupil after viewing an object for one minute with accommodation stimulated 1-2 diopters above their resting focus, their accommodation remained above their initial resting focus for several minutes. In order to find subjects with robust accommodative aftereffects, approximately 20 people were screened. Subject LS was 19, JM was 21, and CR was 26 years of age. Subject LS was myopic, JM was slightly hyperopic and did not have spectacles, and CR was a hyperopic astigmat. They all had normal visual acuities of 20/20 or better, normal stereopsis (20 sec arc), and amplitudes of accommodation over 5 diopters. None reported any problems with asthenopia.

Procedures

The subjects' pupils were dilated with two drops of phenylephrine hydrochloride, a weak sympathomimetic drug, spaced five minutes apart. The subjects were in a dimly lit room for 20-30 minutes while the drops took effect so that they would be relatively dark adapted for the experimemt. Their refractive errors were corrected with the stimulus optometer at the start of the experiment. The dark focus

level and pinhole levels of accommodation were also determined at the start of the experiment. The dark focus and monocular pinhole focus were essentially equal at the start of the experiment.

The subjects viewed the DOG target monocularly through the 4 mm pupil. Accommodation was stimulated approximately 2 diopters above the subject's dark focus. At the end of one minute of stimulation the pinhole was inserted and simultaneously the luminance of the target was reduced by adding neutral density filters in front of the projector. The filters used were 0, .4, .7, 1, 1.2, 1.4, 1.6, and 1.9. Accommodation and eye position were recorded for at least 30 seconds and then the process was repeated. The order of the neutral density filters that were added was randomized. The subjects were given frequent breaks so they would not become fatigued. Experimental sessions lasted 60 - 90 minutes. Each subject had at least three experimental sessions so that the decay of adaptation was recorded 5 times at each luminance level. One subject, C.R., was not checked with the 1.6 and 1.9 neutral density filters because he showed the same fast decay as going into the dark with less dense filters.

Gains were computed by measuring the amplitude of accommodative response above the dark focus after 20 seconds and dividing this number by the average response amplitude

of the accommodation above the dark focus during the one minute accommodative stimulus period. Therefore:

$$G = (d - R) / (D - R) \qquad (1)$$

G = gain

d = level of accommodation at any time, t

D = response accommodation during stimulus period

R = accommodative rest state (dark focus)

The decay of accommodation had an exponential form. The equation for an exponential decay is:

$$d = (D - R) \exp(-at) + R \qquad (2)$$

a = decay constant

After rearranging,

$$(d - R)/(D - R) = \exp(-at) \qquad (3)$$

$a = 1 / T$ where T is the time constant

By substitution,

$$G = \exp(- t / T) \qquad (4)$$

Solving for T,

$$T = -t / \ln G \qquad (5)$$

This formula was used to calculate time constants (T) for the exponential decay using the measured gain at time t.

Results:

The normal decay of unadapted accommodation is rapid when the accommodative loop is opened. Figure 1. b. plots the decay of a 2 diopter accommodative response maintained for 60 seconds when a pinhole is placed before the open eye. This subject (PB), does not have an adaptation response by accommodation. The accommodative response is reduced to the dark focus in 2 seconds after placement of the pinhole. This response is quite similar to the accommodative response when the subject is placed in the dark (figure 1.a). Accommodation quite quickly goes to the dark focus (2 seconds). Using a similar apparatus, Baker et al. (1983) estimated the time constant for decay to the dark focus to be about 1 to 3 seconds. The duration of accommodative aftereffects for subjects LS, JM, and CR are longer than most subjects. Following adaptation to a 1 diopter stimulus for 60 seconds, the pinhole is added, and the accommodation is sustained for over 2 minutes.

When these subjects were put in the dark after 1 minute of accommodative adaptation to a 2 diopter stimulus, the accommodative response drops to dark focus within 20 seconds, with the exception of subject JM. JM demonstrated adaptation of accommodation in the dark. Figures 2-4 plot the gain of accommodation, as defined in formula (1), 20 seconds after the accommodative loop was opened with a

pinhole and luminance reduced with different neutral density (ND) filters. For these subjects, the gain of accommodative aftereffect 20 seconds after the pinhole is added and the luminance is decreased to .2 cd/m^2 (.4 ND filter) from the initial .5 cd/m^2, the accommodation aftereffect approaches nearly 100%. At .01 cd/m^2 (1.6 log units reduction in luminance), the accommodative level after 20 seconds has typically reached the level achieved when the subjects are put into darkness. For neutral density filters in between the initial luminance and a luminance that gives a dark response, there is an intermediate adaptation. Accommodation is decreased at 20 seconds but not to the dark focus. It appears that the rate of decay of accommodation as well as the amplitude of the aftereffect, depends on the luminance level. The amount and duration of adaptation decrease gradually with decreases in luminance level.

Figure 5 plots the accommodative level at 3 luminance levels for subject LS. She was put in the dark after a 1 minute period of simulation of accommodation. Accommodation dropped rapidly to the dark focus. When luminance was increased to .2 cd/m^2 by switching to the .4 N.D. filter, with the pinhole still in place, accommodation increased to the adapting stimulus level. At the arrow marked 1.9 luminance was reduced to .006 cd/m^2 (1.9 N.D. filter), and accommodation decreased as rapidly as when she was put in the dark. Increasing the luminance to .2 cd/m^2, again

caused accommodation to increase to the adapted level. This shows that darkness and a reduction of luminance to .006 cd/m^2 both mask the adapted response of accommodation.

The decay of accommodation is approximately exponential. However, the decay is not smooth and there are fluctuations of up to 1 diopter. In table 1, time constants (T) are calculated based on a decaying exponential curve fit to the accommodative aftereffect at time 0 and 20 seconds using the formula (5) shown above. The gains at 20 seconds were used because if the time constant was longer than 5 seconds, then significant gains would still be present 20 seconds after opening the accommodative loop (e.g. t = 5 seconds, gain = .018). As luminance level is decreased, the time constant shortens. These calculated time constants agree well with the actual data. Therefore, adaptation can be thought of as increasing the decay time constant of accommodation. As luminance decreases the adaptation level decreases and the time constant shortens. Figure 6 shows recordings of the decay of accommodation for subject LS following 1 minute of stimulation of accommodation after a pinhole and different N.D. filters were added at time 0. The higher the luminance, the longer the accommodation was sustained and the longer the time constant for the decay, after opening the accommodative loop. With a .4 neutral density filter added there was nearly full adaptation of accommodation for the full 40 seconds. As luminance was

reduced, less of the adapted response appeared. However thinking of adaptation solely in terms of time constants is misleading because an increase in luminance also causes an increase in the accommodative level.

If luminance is varied after the eye is adapted, decreases in luminance cause the accommodative aftereffect to drop and increases in luminance cause it to rise. Figure 7 shows that accommodation decreases when luminance is dropped and rebounds when luminance is increased again (A and B). We also found the decay of tonic accommodation to be interrupted by darkness (figure 5) as Schor et al. (1986) reported. Thus the level of adaptation appears to vary with luminance level.

Adaptation of accommodative vergence

Stimulation of accommodation can cause adaptation of vergence by way of the crosslink interaction between accommodation and vergence. The time course for the decay of accommodative vergence was usually similar to the decay of accommodation. However, on some occasions, accommodative vergence would decay much more rapidly than accommodation. The different luminance levels could further disrupt the usual synergy between accommodation and vergence. This dissociation suggests that there are separate adaptable elements for accommodation and vergence as demonstrated

previously by Kotulak and Schor (1986) and by Schor and Kotulak (1986).

Adaptation of dark vergence

Vergence adaptation is often measured as adaptation of the phoria in the light (Schor 1983). Differences between light and dark vergence adaptation levels that paralleled the differences in the adapted light (pinhole) focus and adapted dark focus were sought. In one case, the adapted level of dark vergence (6 prism diopters) was not altered by switches to the dark (fig. 8). For this subject, PB, the monocular pinhole vergence was equal to the vergence in darkness. With a switch to darkness, her accommodation decayed rapidly to the dark focus, but her vergence did not change. The accommodative change was dissociated from the vergence change. With a switch back to the light, the adaptation of accommodation became manifest again.

In contrast to this subject, several other subjects demonstrated a difference in their vergence under a monocular pinhole condition and their vergence in the dark. Similarly, Alpern and Larson (1960) found an increase in convergence when the light level is below photopic levels that may be due to an increased tonic convergence. If these subjects were looking at a target monocularly through a pinhole and then switched to the dark, they would show an increase in vergence, often without a concomitant increase

in accommodation. For subject CS, vergence would increase
about 10 prism diopters after about 15 seconds (figure 9.
a.). This might be analogous to the difference between
adapted accommodation and the dark focus. However, in this
case, the vergence in the light is for a more distant
position than his vergence in the dark. Repeated switches
to the dark caused repeated increases in vergence (figure 9.
b.). This case seems similar to the above switch for
accommodation, however, vergence increased much more slowly
in switches to the dark than switches back to the light.
For accommodation, switches to the dark caused a rapid
change of accommodation to the dark focus. Subject CS,
always showed high adaptation of his monocular pinhole
vergence after a convergence stimulus of 1 minute, however
this adaptation did not change his dark vergence. In
contrast, subject PB shown in figure 8 did retain adapted
phoria states in darkness.

In summary, adaptation of vergence causes a shift in
dark vergence in some cases and not in others. With
switches to the dark, the accommodation and vergence changes
can be quite dissociated. More investigation of these
changes and the effect of adaptation on the dark vergence
and dark accommodation needs to be done.

Discussion:

A comparison of open loop methods to manifest accommodative aftereffects

This study demonstrates that the magnitude of adapted accommodative response can be quite large if the accommodative loop is opened with a pinhole pupil as opposed to darkness. Studies that use darkness to reveal adaptation of accommodation have required sustained periods of adaptation, much longer than our 1 minute adaptation period, and the effects have been modest and relatively short lived (Schor et al. 1984, Wolf et al. 1987). In addition, the luminance of the target has an effect on the level of accommodative adaptation. If accommodation is measured with a technique that illuminates the retina, such as a laser optometer, though not providing a blur stimulus to accommodation, the technique could conceivably reveal some level of accommodative aftereffect that would otherwise be masked in darkness. Kothe et al. (1987) found that measures of dark focus of accommodation showed considerable variability for some individuals when laser speckle exposure duration was increased. Perhaps the larger exposure times are revealing tonic aftereffects of accommodation that are masked in darkness.

In evaluating accommodative effects from adaptation, the pinhole method of opening the accommodative loop may be more valuable than darkness. The open loop pinhole tonic

accommodation level may be the tonic accommodative level that influences the accommodative response in photopic binocular conditions. Using darkness to reveal the level of adaptation may be misleading because the real level of tonic accommodation may be masked by darkness. Schor et al.'s (1986) proposed model with a light dependent variable gain element for accommodation predicts that full effects of tonic accommodation are only evident under photopic conditions.

The dark focus of accommodation can be modified in some subjects by adaptation. One subject, JM did show an increased dark focus after adaptation, but the accommodative aftereffects were larger under photopic conditions. This change in dark focus is the same type of response that has been reported in a number of other studies (Schor et al. 1984, Wolf and Ciuffreda 1987). In this subject, the adapted dark focus was equal to the pinhole focus when luminance was reduced with the 1.6 or 1.9 neutral density filter. At slightly higher luminance levels, the accommodative response present varied with luminance level.

Comparison of luminance levels for the accommodative response to defocus and accommodative aftereffects

Schor et al. (1986) proposed some sort of light dependent variable gain element for adaptation of tonic accommodation. Our results indicate that the gain is

dependent within limits on the luminance. For a 1.9 neutral density reduction of luminance of our target, the luminance was .006 cd/m^2. For a 1.0 neutral density filter the luminance was .05 cd/m^2. Campbell (1954) found a critical luminance of approximately 1 microlambert (.003 cd/m^2) for a test object subtending 1 degree that was necessary to activate the accommodative reflex. Johnson (1976) found accommodation assumed its dark focus value at .051 cd/m^2. Our values agree approximately with these studies and indicate that perhaps the stimulation of cones is needed to elicit an accommodative response or else the accommodative aftereffect goes to a dark focus bias level. However, our results also indicate that in an open loop pinhole condition, stimulation of the cones causes the adaptation of accommodation to become manifest.

Proximal accommodation

It is unlikely that proximal effects could account for the difference in adaptation for the pinhole and darkness open loop conditions. The DOG target did not change in size and the subjects did not report any perceptual changes in target distance. However, dimmer targets were associated with decreased accommodation. This aerial perspective might possibly be a cue to distance. The persistence of accommodative aftereffects in a lighted field (Schor,

Kotulak, and Tsuetaki 1986) is further evidence against proximal effects.

Proximal vergence

On the other hand, while dark vergence was not primarily studied in this investigation, proximal effects might be affecting vergence in darkness independently of accommodation. When put in darkness, several subjects demonstrated increased vergence independent of increasesd accommodation. Similarly, Alpern and Larson (1960) reported an increase of vergence independent of accommodation as luminance was reduced to scotopic levels. We speculate that this increased vergence might be some form of proximal vergence. This increased vergence in the dark was variable and decreased in some cases with repeated switches into the dark. Epstein (1967) found there were many factors influencing judgement of distance, even in total darkness. Observers imagine the extent of the space that they are in and their perceptions or at least their estimates of distance are adjusted to fit this imagined space. Dark vergence may vary with perceived distance. Indeed, subjects with the largest dark vergence perceived darkness boundaries within several inches from their face while subjects who did not increase in dark convergence from the light phoria perceived darkness boundaries at several meters away from their face. Furthermore, it appears that those subjects who

had minimal dark proximal vergence had prism vergence aftereffects in both the light and the dark whereas those with large amounts of dark convergence did not manifest prism adaptation aftereffects in darkness. Perhaps proximal vergence supersedes or supplants vergence aftereffects. Dark vergence and its relation to the adapted vergence level in the light need more study.

Depth of focus with pinhole

The responses that were obtained with the pinhole in place were similar to those that would be expected if accommodation were closed loop and luminance was markedly reduced. Therefore, it might be argued that perhaps the pinhole was not adequate in opening the accommodative loop. This was ruled out by reducing the accommodative stimulus to zero when the neutral density and pinholes were added. Doing this did not influence the decay of accommodation after adaptation. In addition, changing the accommodative stimulus with the pinhole in place did not have any effect on the open loop accommodative response. Similarly, Ward and Charman (1987) have shown that a .5 mm pupil effectively opens the accommodative loop.

Target visibility

It should be remembered that as luminance level is reduced, the resolvable detail and contrast gradient are also reduced. It may be that one of these factors rather

than luminance level may be the factor causing the different levels of accommodative aftereffects. However, the report by Schor, Kotulak, and Tsuetaki (1986) and Wolfe and O'Connell (1987) of a difference in dark and empty field resting levels for some subjects ("superadapters"), suggests that luminance level is the determining factor. An experiment with empty fields at different luminance levels would help resolve this question.

Interactions between accommodative aftereffects and the response to defocus

The results suggest that with accommodation closed loop (a natural pupil), if the subject is adapted to an accommodative stimulus for a few minutes and luminance is reduced to mesopic levels or the target is very blurred, then accommodative aftereffects will be present and accommodation will more slowly drift to the usual dark tonic accommodative level that was present before adaptation. A very blurred target can effectively remove the stimulus to accommodation (Heath 1956). In fact, removal of the pinhole with luminance reduced did not result in a quick reflex change in accommodation to the stimulus value.

These aftereffects may also drag down or restrict accommodative response to a photopic stimulus. For example, subject LS would be slow to change her accommodation to the dioptric stimulus level after several adaptation periods

even when the luminance was increased. Tonic adaptation may on occassion be the cause of reported spasms of accommodation or poor accommodative facility.

Now, the question is, how does the variability in accommodative aftereffects with luminance level influence the accuracy of accommodation under normal binocular conditions. The tonic level of accommodation may be variable under mesopic luminance levels. Accommodation may be biasd toward any level that it has sustained for several minutes rather than being biased toward the usual dark focus.

Summary

In subjects who show high adaptation of accommodation to lenses, at mesopic luminance levels the rate of decay of the adapted accommodation to the resting focus is dependent on the luminance level. The rate is faster as scotopic conditions (.001 cd/m^2) are approached. The accommodative aftereffect revealed by opening the accommodative loop with a pinhole is generally greater than that revealed when the accommodative loop is opened with darkness.

Fig. 1. a. Decay of accommodation for subject PB in darkness after 1 minute of monocular stimulation (2 diopters) of accommodation above the dark focus. The decay is rapid and reaches dark focus 2 seconds after placement of the pinhole. b. Decay of accommodation when pinhole is added after 1 minute of the same adapting stimulus. The decay is rapid and very similar to the decay when placed in darkness. This is in contrast to the three "good adapters" studied who showed very slow decay of accommodation after just 1 minute of stimulation.
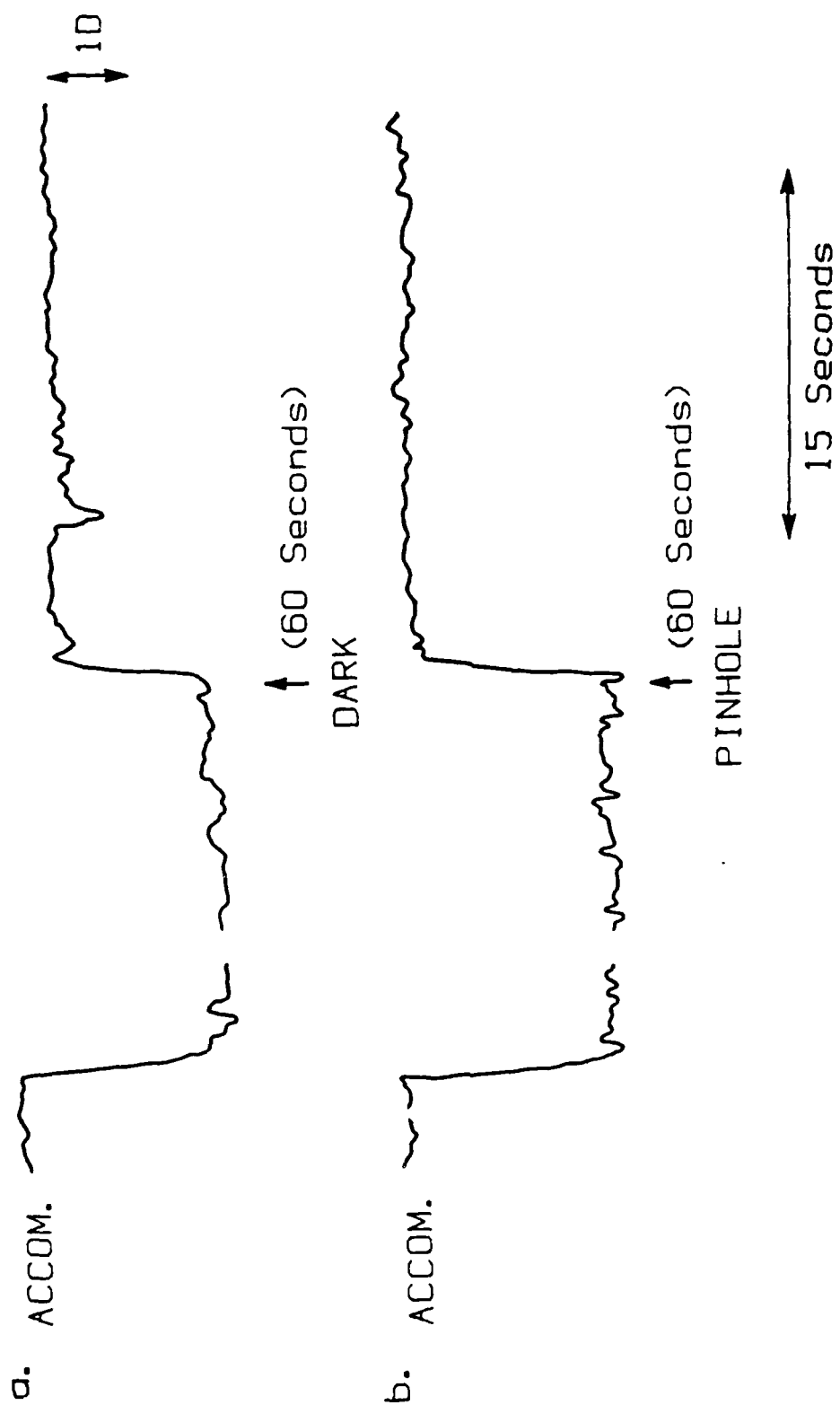
Figs. 2-4. Gain of accommodation is shown for three subjects at different luminance levels, 20 seconds after the accommodative loop is opened with a pinhole. Subjects were adapted by stimulating accommodation for 1 minute approximately 2 diopters above their dark focuses. The gains are computed by dividing the amount of accommodation above the dark focus, at 20 seconds after the pinhole and filter are added, by the average adapting level of accommodation. The gains are the averages of 5 trials. The luminance was 0.5 cd/m^2 for the zero neutral density filter. Error bars show one standard deviation.

CR
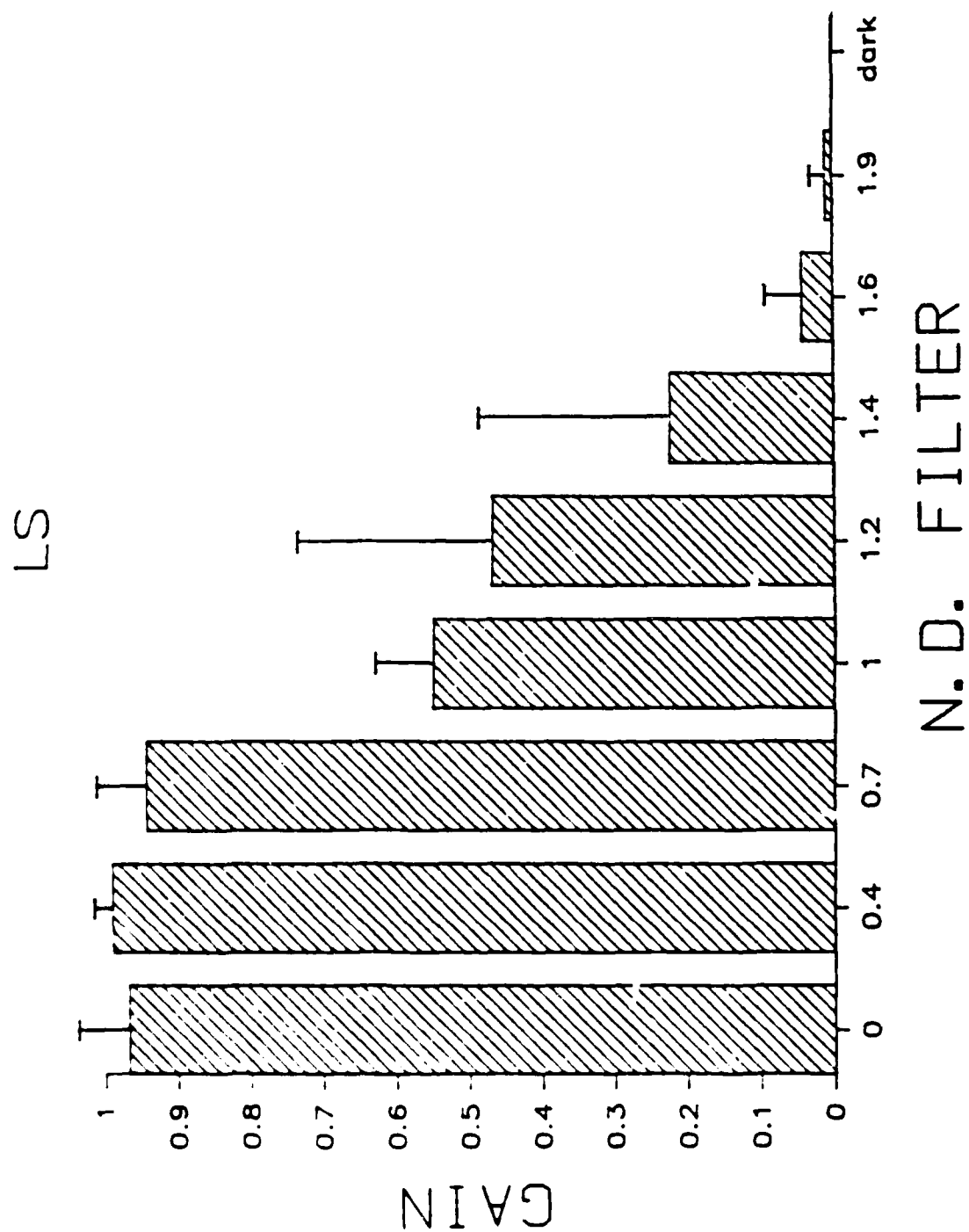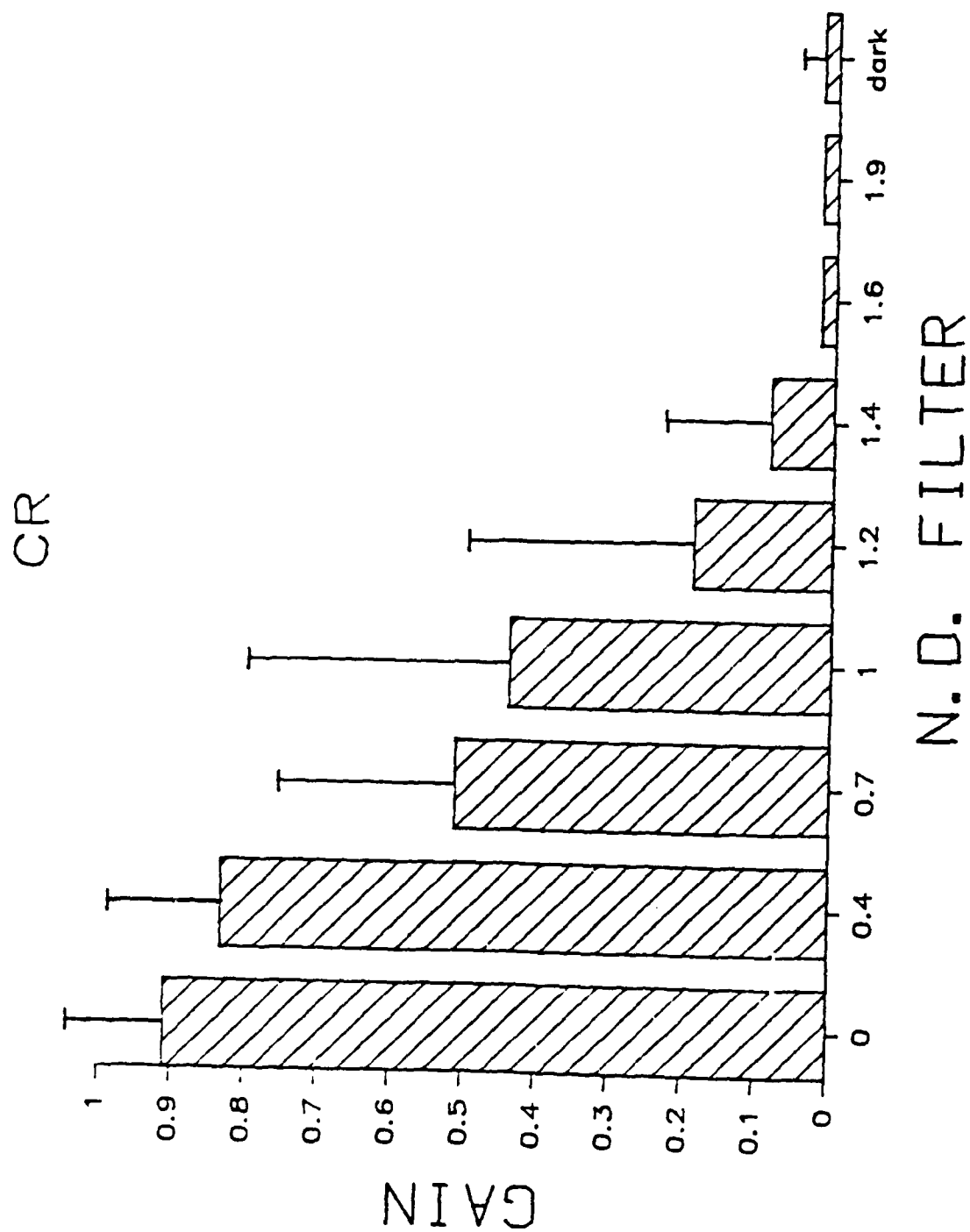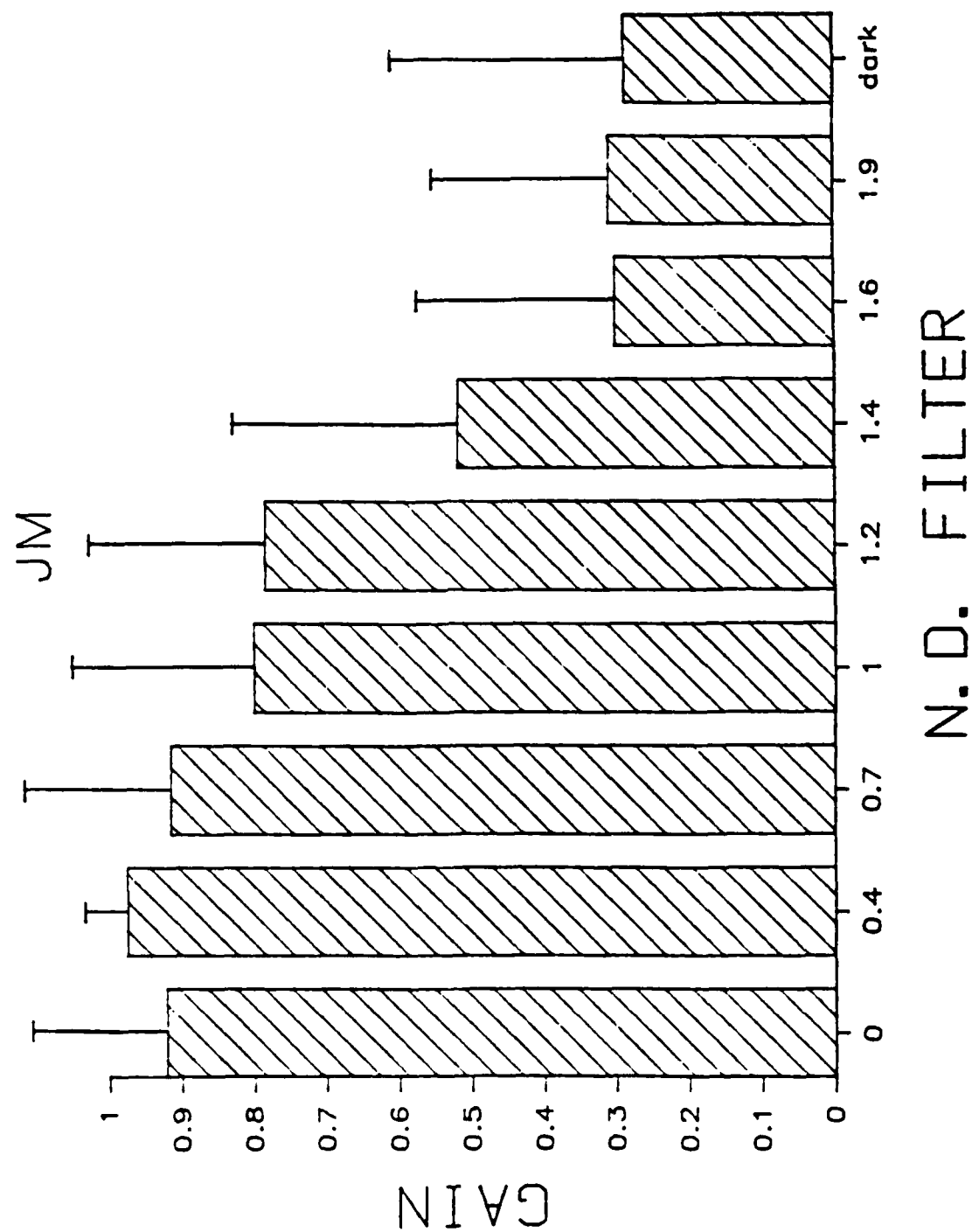
Fig. 5. Decay of accommodation for adding 1.9 neutral density filter (.006 cd/m^2) and pinhole compared to going into the dark. There is a similar rapid decline of accommodation in both cases. When luminance is increased by switching to a .4 N.D. filter (.2 cd/m^2) with the pinhole still in place, the accommodation increases. This shows that darkness and the 1.9 N.D. filter are masking the tonic adaptation of accommodation. Increases in accommodation are in a downward direction.

ACCOM.

DF

1D

DARK

.4

1.9

.4

15 Seconds

164
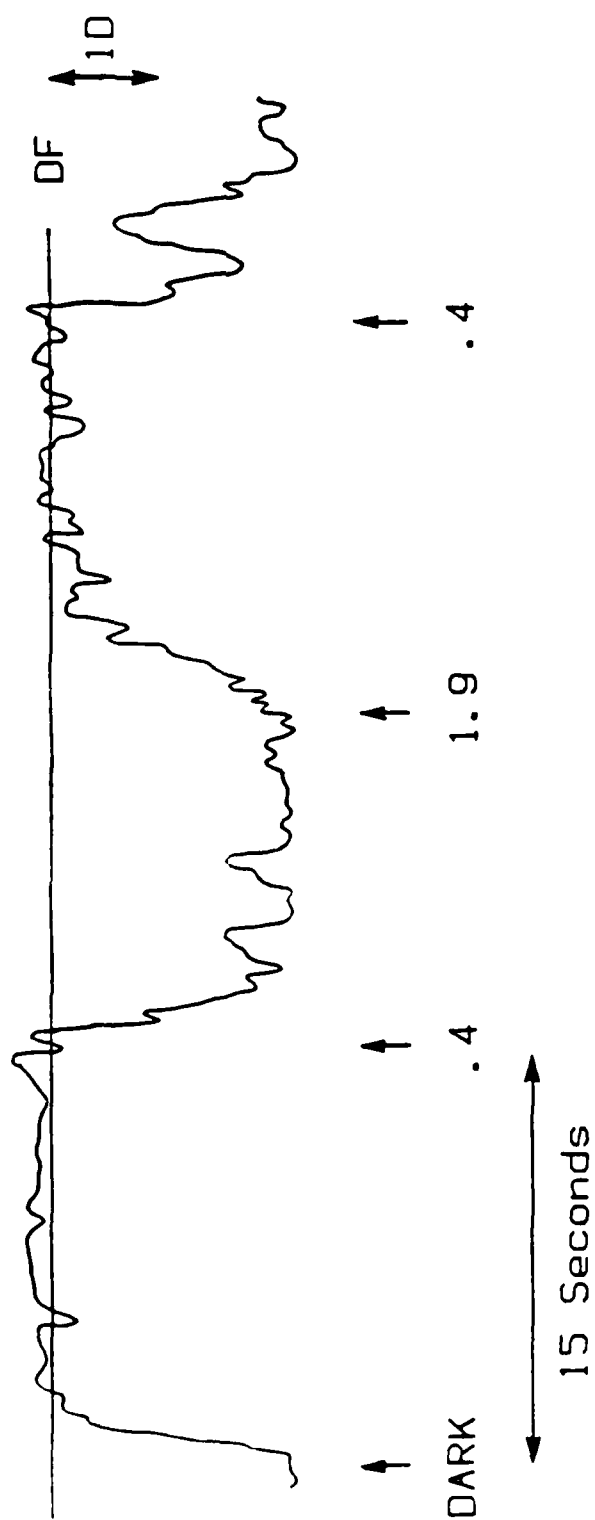
Fig. 6. Subject LS. Recordings of decay of accommodation after 1 minute of stimulation of approximately 2 diopters of accommodation for 5 luminance levels. At time 0, the pinhole and neutral density filter were added. The higher the luminance, the longer the accommodation was sustained and the longer the time constant for the decay after opening the accommodative loop .

166
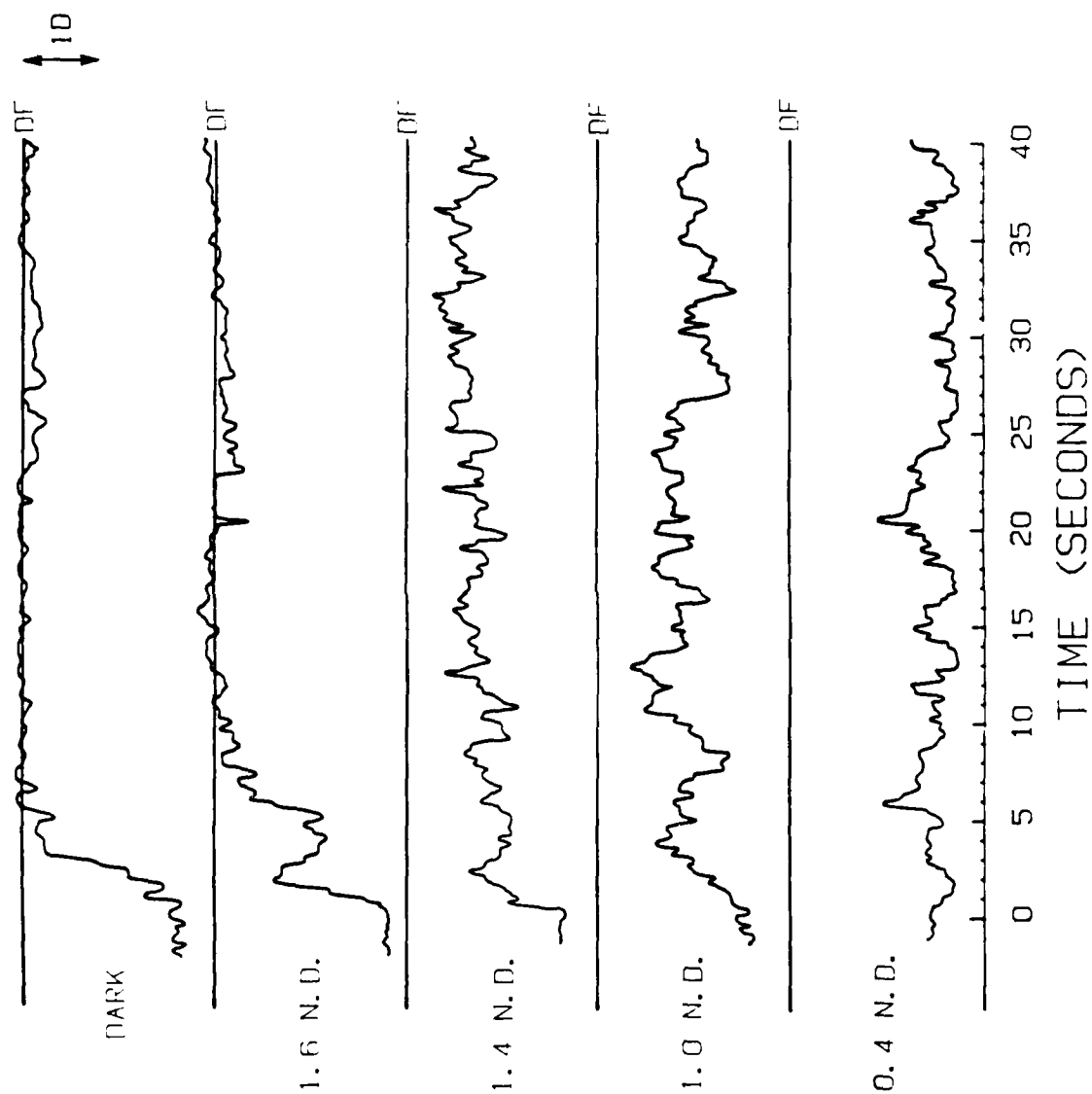
Fig. 7. Changes in neutral density filters. This subject
was stimulated to 2 diopters of accommodation above the dark
focus and a pinhole and .4 N.D. filter were added. At A,
the filter was changed to a 1.0 N.D. filter and
accommodation dropped to an intermediate level. At B, the
luminance was increased by switching back to a .4 N.D.
filter. Accommodation dropped momentarily but then
increased to its previously adapted level. The increase in
filter density partially masked the adaptation of
accommodation. The line labeled DF is the dark focus level.
Increases in accommodation are in a downward direction.

ACCOM.

DF

1D

B

A

15 Seconds

168
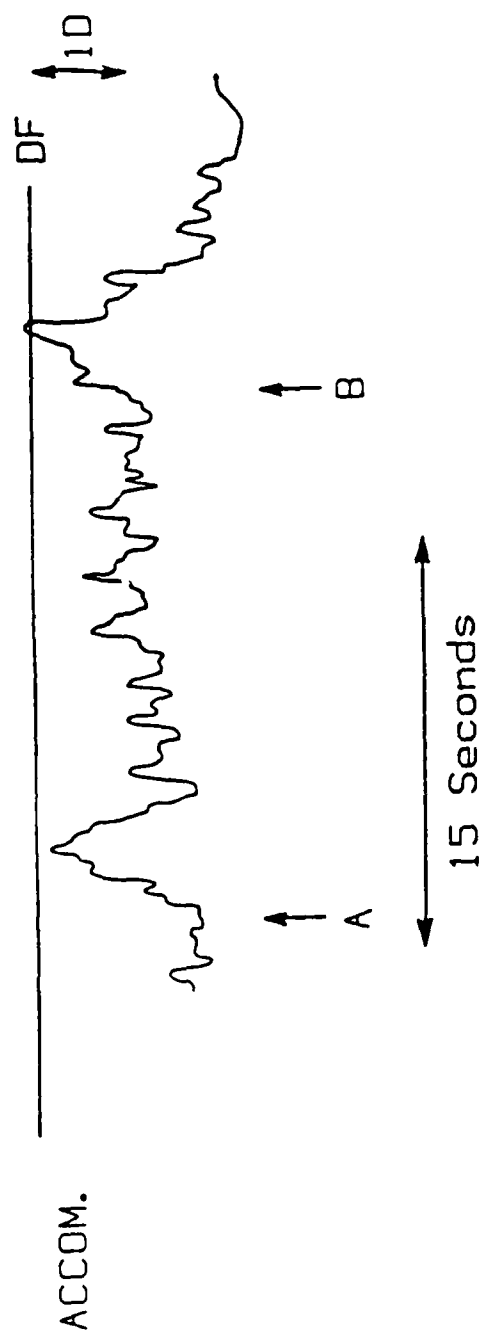
Fig. 8. The decay of tonic aftereffects of accommodation and vergence during open loop (monocular pinhole) conditions interrupted by brief periods of darkness (underlined segments). Adaptation was for 2 minutes to a 2 diopter accommodative stimulus. During dark periods, accommodation went to its resting focus while the vergence aftereffect continued its slow decline. Changes in vergence were not coupled with changes in accommodation. Tonic adaptation of accommodation was masked in darkness, but vergence adaptation was not masked. The pinhole was added at point B. Increases in accommodation and vergence are in a downward direction. The resting levels of accommodation and vergence were the levels before accommodation was stimulated at point A.

a. ACCOM.

b. VEG.

171
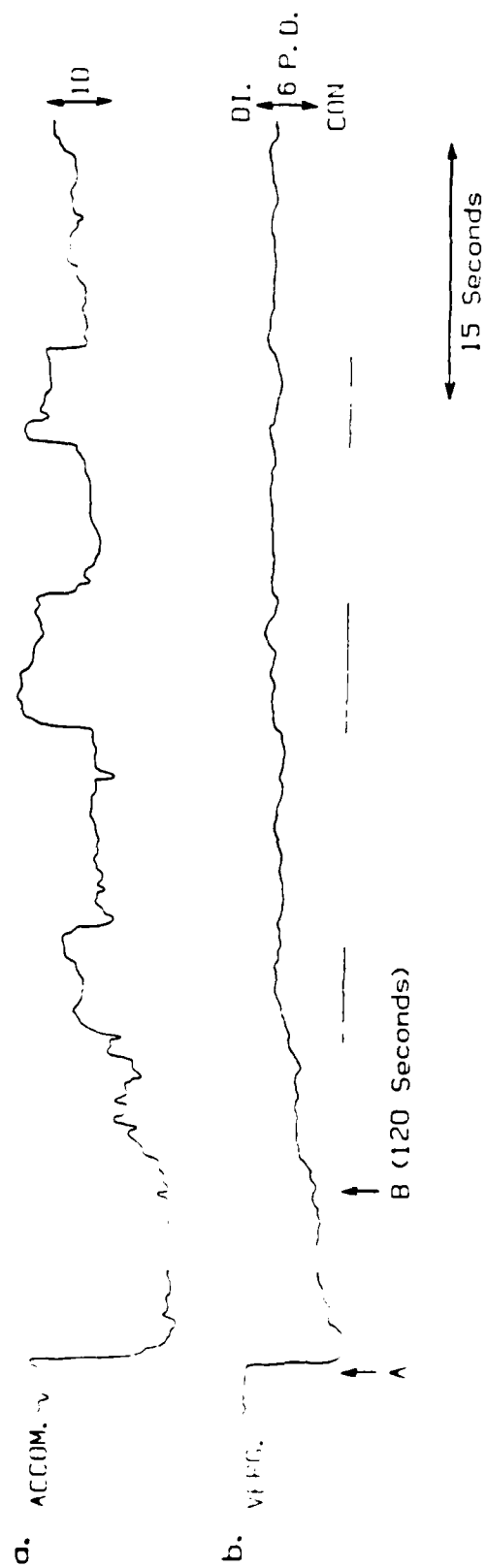
Fig. 9. a.   Record of vergence for CS when switched from

monocular pinhole condition to darkness at point A.   The

vergence slowly increased convergence about 10 prism

diopters. When switched back to the pinhole at point B,

vergence decreased to its original level for this monocular

pinhole condition. b. Frequent switches to darkness from

monocular pinhole condition results in slow increases in

vergence in darkness and rapid divergence when switched to

pinhole. Underlined areas mark periods of darkness. This

is in contrast to PB in figure 8 who did not show switches

in darkness.

a.

b.

15 Seconds

1.4
6.7
1.0
1.2
1.4
1.6
1.9
dark

.05
.01
0

. . . . Verxence and
. . . . . . luminance quantity on the
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Chapter 5

Conclusion

Disparity is a stimulus to vergence primarily and to accommodation secondarily through the CA/C crosslink, while defocus blur is a stimulus to accommodation primarily and vergence secondarily through an AC/A crosslink. In this thesis, changing size or "looming" has also been shown to stimulate accommodation and vergence, accommodation primarily and vergence secondarily.

Voluntary effort has similarly been shown to stimulate accommodation primarily and vergence secondartily through an AC/A crosslink. These results necessarily imply that in a natural environment, disparity and blur are not the only inputs that should be considered in analyzing accommodation and vergence and their interactions. Blur and disparity may be adequate stimuli, but they are not the only stimuli to accommodation and vergence. Reduction experiments which eliminate all cues except for accommodation and vergence may be misleading in any determination of which system, accommodation or vergence, is the primary system in a natural environment.

Combining changing size (looming) with changing blur or changing disparity increases the accuracy and reduces the phase lag of the accommodative and vergence responses

(Erkelens and Regan 1986, Kruger and Pola 1986). Voluntary effort may be a component of these responses of accommodation and vergence. Thus secondary inputs to accommodation and vergence should be included in models describing accommodation and vergence responses. Furthermore, it may be easier to train or develop a normal accommodative response in environments with multiple cues rather than reduced cues which only vary blur as a stimulus.

In evaluating the relation of accommodation and vergence to each other, there are also other factors to consider. The effect of tonic adaptation of accommodation and vergence can dissociate the changes in accommodation and vergence described by the AC/A and CA/C ratios. In addition, luminance has been shown to be an additional factor that influences the level of tonic adaptive accommodation. As luminance is reduced to mesopic levels, when accommodation and vergence are open loop (monocular pinhole), the tonic adaptation of accommodation will be progressively masked. This tonic adaptation of accommodation, which may be masked by experiments that open the accommodative with darkness, needs to be considered in experiments that might cause adaptation of accommodation or vergence.

Schor's model of accommodation and vergence with independent and separate dual crosslinks provides a useful heuristic tool for examining accommodation and vergence.

aftereffects can be explained by a variable gain element that depends on luminance. The response of accommodation and vergence to changing size or voluntary effort in a rate like the blur driven AC/A ratio is explained by these stimuli having an input to accommodation before the AC/A crosslink.

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